A High-Accuracy Electronic Pressure Transducer with a Wide Temperature Range and Single Iteration Temperature Calibration

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Abstract: - This article reports the development of a solid state pressure transducer for use in the measurement of blood pressure. It is intended to act as a replacement gauge for the mercury and aneroid manometers used in conventional sphygmomanometers. It measures pressure in the range 0-300mmHg (0-40kPa) with a resolution of 1mmHg (0.13kPa) and an accuracy of \pm 1mmHg (\pm 0.13kPa) which is displayed on a liquid crystal display. It operates from a 9V PP3 battery over a temperature range of -20 to +60°C. It is fully temperature compensated and can be calibrated in a single temperature cycle.

Key-Words:- Pressure Transducer, Electronic Manometer, Blood Pressure Measurement, Sphygmomanometers, Temperature Compensation.

1 Introduction

Human blood pressure is measured using a sphygmomanometer. This instrument consists of a compression cuff wrapped around the subject's arm, a stethoscope to listen to arterial sounds and a manometer used to indicate the pressure in the cuff. The manometer may be of the mechanical aneroid type with a dial, or of the mercury-filled type having a columnar display.

A survey carried out some years ago by one of the authors showed that a large percentage of the aneroid and mercury sphygmomanometers in use in hospitals and general practice in the Rep. of Ireland were inaccurate [1]. In the case of aneroid devices, the inaccuracies were large and were caused by the inherent mechanical limitations of these types of manometers, combined with lack of regular maintenance and, in some cases, rough treatment. In the case of mercury devices, the inaccuracies were much lower and were due almost entirely to the lack of maintenance commensurate with their high frequency of usage. While intrinsically accurate when properly maintained, mercury devices suffer from all of the risks associated with toxic chemicals and maintenance must usually be carried out by professionals.

The use of mercury in instruments in which it can be replaced with a suitable alternative has already been discontinued in Sweden, Canada and many parts of the USA [2-4]. The use of mercury sphygmomanometers is currently being phased out in many European countries on a voluntary basis but this process is likely to become mandatory in the near future. This has led to the introduction of a wide and varied range of fully and semi-automatic electronic sphygmomanometers to the market.

Many of these devices do not meet high clinical standards and are consequently viewed with suspicion by much of the medical profession [5,6], whose preference is still for a manually carried out measurement in clinical situations. Meanwhile, aneroid sphygmomanometers continue to be used as portable instruments in the doctor's case, despite their limitations. In fact, in many hospitals, aneroid manometers are being used in larger wall-mounted form to replace mercury manometers, even though not as accurate in the long term [7-9].

This article reports the development of an electronic pressure gauge that can be incorporated into existing sphygmomanometers to act as a suitable replacement for the traditional aneroid or mercury gauges, providing an accurate indication of the cuff pressure during the measurement of blood pressure. It will not alter the clinical auscultatory procedure used by the physician. This allows the superior accuracy of electronic technology to be exploited, while at the same time addressing the reservations expressed by physicians. The design presented improves on a previous version in providing operation over a wider temperature range

and a single-iteration calibration cycle. The earlier design used a voltage based compensation method [10,11], while the revised version uses a current-based method of providing the temperature compensation over a wider range.

2 Background

Blood pressure is usually cited in mmHg and sphygmomanometer gauges normally cover the pressure range 0-300mmHg (0-40kPa) with a resolution of 1mmHg (0.13kPa). A gauge accuracy of ± 1 mmHg is desirable. The electronic manometer presented in this paper uses a solid-state silicon pressure transducer, SX15, (SensorTechnics, GmbH), having the physical construction shown in Fig. 1. The transducer is fabricated as a piezoresistive sensor in the form of a Wheatstone bridge consisting of four ion-implanted resistors on an integral silicon diaphragm which transform the shear stress due to applied pressure into an electrical output. The transducer is packaged in a housing which can be mounted firmly on a printed circuit board or other similar surface, and the pressure connection made with suitable tubing which pushes on to the pressure input ports shown. The transducer is capable of differential pressure measurement but for measurement of gauge pressure one port is simply left open to the ambient atmosphere. The performance characteristics of the transducer are summarised in Table 1 for a bridge supply voltage of 12V but it can operate comfortably down to less than 3V.



Fig. 1 The SX15 pressure transducer

Table 1.Performance Characteristics of SX15 PressureTransducer at $V_B = 12V.$

Parameter	Min.	Typ.	Max.	Unit	
Pressure Range:	0	-	100	kPa	
Supply Current:	-	2.7	-	mA	
Full-scale Span:	75	110	150	mV	
Sensitivity:	750	1100	1500	μV/kPa	
Offset Voltage:	-35	-20	0	mV	
Offset T. C.:	-	+48	-	$\mu V / C$	
Sensitivity T.C.:	-2400	-2150	-1900	Ppm/ ^O C	
Bridge Resistance:	-	4.65	-	KΩ	
Resistance T.C.:	+690	+750	+810	Ppm/ ^O C	
Lin & Hys Error:	-	<u>+</u> 0.2	<u>+</u> 0.5	%FS	

The bridge is exited using an external supply voltage as shown in Fig. 2. The differential output of the sensor is given ideally by:

$$V_{\rm OUT} = \frac{\Delta R_{\rm B}}{R_{\rm B}} V_{\rm B} \tag{1}$$

where ΔR_B is the change in the resistance, R_B , of an arm of the bridge, which is proportional to the applied pressure and V_B is the bridge supply voltage.



Fig. 2 The pressure transducer bridge arrangement

If a span sensitivity, S, is specified for the transducer as the output voltage in mV per unit of supply voltage, per unit of applied pressure i.e. $(mVV^{-1}kPa^{-1})$, then the transducer output can be expressed as:

$$V_{OUT} = S.p.V_B$$
(2)

where p is the applied pressure.

In practice, there are large deviations from the ideal in the transducer characteristics, as can be seen in Fig. 3. The bridge output is not zero for zero applied pressure, but an offset voltage, V_{os} , exists which has an associated range due to manufacturing variations.



Fig. 3 Typical pressure transducer characteristics

Similarly, the transducer sensitivity has a manufacturing tolerance so that the full scale span at a nominal bridge voltage lies in a range between maximum and minimum values. In addition, both the offset voltage and the sensitivity vary with temperature and consequently have associated temperature coefficients. To complicate matters further, the transducer characteristic has some degree of non-linearity over its range of operation and deviates from the ideal straight-line output voltage vs. pressure relationship. Finally, properties such as hysteresis and ageing effects can also give rise to measurement errors.

3 Design Considerations

If the nominal characteristics of the transducer are quoted at a reference temperature T_0 , typically 25°C, and a bridge voltage V_{B0} , then the output voltage from the non-ideal transducer in practice is given as:

$$V_{OUT} = S_0 [1 + \alpha (T - T_0)] V_{B0} p$$

+ $V_{OS0} [1 + \beta (T - T_0)]$ (3)

where:

 S_0 is the transducer sensitivity at temperature T_0 , V_{B0} is the bridge supply voltage,

 V_{OS0} is the offset voltage at temperature T_0 , p is the applied pressure,

 α is the temperature coefficient of the sensitivity,

 β is the temperature coefficient of the offset voltage T is the operating temperature.

If, on the other hand, the transducer is fed from a current source, I_{B0} and the total resistance of the bridge as seen by the current source is R_{B0} , then the output of the transducer including temperature

variations in the bridge resistance accounted for by the temperature coefficient γ is given as:

$$V_{OUT} = S_0 [1 + \alpha (T - T_0)] I_{B0} R_{B0} [1 + \gamma (T - T_0)] p + V_{OS0} [1 + \beta (T - T_0)]$$
(4)

The offset voltage can be counteracted by adding a cancellation voltage, of equal magnitude and opposite polarity to that of the offset, to the output from the bridge in a signal conditioning amplifier. This cancellation voltage must also have a temperature coefficient equal to that of the offset voltage. Variations in the sensitivity can be corrected by making the gain of the signal conditioning amplifier adjustable to give the desired full-scale output voltage.

This leaves only the temperature variations in sensitivity to be corrected for. This is achieved by arranging for the bridge supply current to change with temperature in a direction opposite to that of the transducer sensitivity, so that the resulting output voltage vs. pressure after conditioning becomes independent of temperature. In this case, the composite output voltage from the signal conditioning amplifier can be described as:

$$V_{OUT} =$$

$$GS_{0}[1 + \alpha(T - T_{0})]I_{B0}[1 + \varepsilon(T - T_{0})]R_{B0}[1 + \gamma(T - T_{0})]p + V_{OS0}[1 + \beta(T - T_{0})] + V_{OC0}[1 + \delta(T - T_{0})]$$
(5) where:

 V_{OC0} is offset cancellation voltage at temperature T_0 , δ is the temperature coefficient of the offset cancellation voltage,

 ϵ is the temperature coefficient of the bridge supply current and the other parameters are as above.

The aim is to obtain a fully temperature compensated and corrected signal after conditioning such that:

$$V_{OUT} = GS_0 I_{B0} R_{B0} p \tag{6}$$

This is accomplished by making $V_{OC0} = -V_{OS0}$, $\delta = \beta$ and $\varepsilon = -(\alpha + \gamma)$ in order to counteract first order temperature associated variations. If these conditions are substituted into equation (5), the resulting output after signal conditioning is:

 $V_{OUT} = GS_0 I_{B0} R_{B0} p[1 - (\varepsilon^2 + \alpha \gamma) \Delta T^2 + (\alpha \gamma \varepsilon) \Delta T^3]$ (7) where $\Delta T = T - T_0$ is the deviation in operating temperature from the nominal value, T_0 . This shows that there is a residual error in the output of the signal conditioning amplifier, which is dependent on the temperature coefficient of the transducer sensitivity and the bridge resistance as well as the extent of the operating temperature range. Table 1 gives the highest value of α as -2400ppm/°C for the transducer and the corresponding value of γ as +690ppm/°C. If the maximum temperature deviation from T_0 is taken as 25°C, then the worst case error is $\pm 0.04\%$ which at full scale span is a corresponding error in pressure of ± 0.12 mmHg. This is well below ± 0.5 mmHg which is the minimum error which will register on the display with a digital resolution of 1mmHg. The combined worst-case hysteresis and non-linearity error is given in Table 1 as +0.5% of full-scale pressure. However, in measuring blood pressure, the transducer operates over less than half of its full scale and so the actual error will be considerably less than this. With careful calibration the total measurement error can easily be maintained within +1mmHg (+0.13kPa) over the full operating pressure and temperature ranges.

Temperature compensation circuits pose additional problems in the calibration procedure. Calibration for a limited temperature range is normally carried out as a two-point procedure. Devices used to provide a compensating current or voltage rarely provide zero output at the lower calibration temperature, commonly 25°C. Consequently, calibration becomes an iterative process whereby several iterations of adjustment are necessary to obtain an acceptable degree of accuracy. Fig. 4 shows this procedure applied to the compensation of the temperature dependence of the transducer offset voltage. The compensating voltage is obtained as a combination of a temperature independent component (TIC) added to a temperature dependent component (TDC), so that the combined temperature compensation (CTC) voltage matches the transducer. The temperature dependent component (TDC) when projected backwards on the temperature scale has a zero output at some negative value of temperature, typically absolute zero on the Kelvin temperature scale.



(a) initial adjustment at temperature T₀





(b) initial adjustment at temperature T_1



(d) second adjustment at temperature T₁



TIC: temperature independent component. CTC: combined temperature compensation, TDC: temperature dependent component, Tr: transducer characteristic.

Initially, the non-temperature dependent voltage is adjusted so that the combined temperature compensation (CTC) voltage matches the transducer offset at the lower calibration temperature, T_0 , as shown in Fig. 4(a). The temperature is then raised to the upper compensation point, T_1 and the slope of the temperature dependent component adjusted to match the transducer characteristic at T_1 , as shown in Fig. 4(b). This however, disturbs the match at the lower point so that an error is reintroduced at the lower temperature To. This requires a second adjustment at the lower temperature. The second adjustment at temperature To then disturbs the match at the upper point as shown in Fig. 4(c). A second adjustment at the upper temperature T₁ restores the match at the upper point but reintroduces an error at the lower point as can be seen in Fig. 4(d), though less than on the first adjustment. Several iterations involving repeated temperature cycling may be necessary until the coefficient of the compensating voltage is adjusted to match the temperature characteristic of the transducer at both upper and lower calibration temperatures.

If however, the TDC can be arranged to give zero contribution at the lower temperature, T_0 , then calibration can be achieved in a single iteration as illustrated in Fig. 5. In this case, the TIC is initially adjusted to make the CTC match the transducer characteristic at temperature T_0 , with no contribution from the TDC. Then the temperature is increased to the higher calibration value, T_1 and the TDC is adjusted to get the CTC to match the

transducer characteristic. This does not disturb the match at the lower temperature and hence calibration is accomplished in a single temperature cycle. A similar procedure can be used in the compensation of the temperature dependence of the transducer sensitivity.

4 Circuit Implementation

A schematic diagram of the complete electronic manometer circuit is shown in Fig.6. The circuit is powered from a battery which feeds a 5V regulator, IC_1 , with a low dropout voltage. The buffer op-amp IC_6 is used to generate a -0.5V secondary supply voltage to feed the other op-amps IC_4 and IC_5 which cannot operate from +5V.

The heart of the electronic manometer is the digital panel meter (DPM), IC₇, a MAX138 from Maxim Inc., which is a differential-input, ratiometric DPM, having a very high input common-mode-rejection-ratio, high temperature stable performance, as well as an on-chip positive-to-negative supply converter. It provides a direct drive facility for a $3\frac{1}{2}$ digit liquid crystal display (LCD). The numerical output displayed on the LCD is given as:

$$N = 1000 x \frac{V_{INHI} - V_{INLO}}{V_{REFHI} - V_{REFLO}}$$
(8)

The reference voltage is obtained via a potential divider, R_{16} , R_{17} and R_{V5} , placed across an internal precision voltage reference which exists between the supply rail and the analogue common pin on the DPM, IC₇ pin 32. The potentiometer R_{V5} is used to



Fig. 5Adjustment of the temperature compensation of the transducer offset voltage with a single iterationTIC: temperature independent component,
CTC: combined temperature compensation,TDC: temperature dependent component,
Tr transducer characteristic





adjust the nominal full-scale value on the display at the lower calibration temperature. The other ancillary components connected to IC_7 are selected in accordance with the manufacturer's recommendations for optimum performance.

The SX15 transducer, IC_2 , is driven by a programmable current source, IC₃, the value of which current is set by resistors R_2 , R_3 and the voltage at the output pin 1 of op-amp IC_{4A} . These components are also used to match the temperature coefficient of the current source to that of the transducer in order to provide nominal temperature compensation of the full-scale span over the working range. IC₄ is chosen to have a very low temperature coefficient of offset voltage so that the voltage at pin 1 is essentially temperatureindependent. The input potential to IC_{4A}, which acts as a buffer amplifier, is provided by the potential divider consisting of the bandgap reference diode, ZD_1 , having a very low temperature coefficient, resistors $R_4 - R_7$ and R_{V1} which is used to adjust it. The positive output voltage from pin 2 of the transducer, IC₂, is fed via one side of the low-pass filter comprising of R_{15} and C_8 to the positive differential input pin, IN HI, of the panel meter, IC₇ pin 31. The output voltage from the negative side of the transducer, IC_2 pin 4, is scaled by a factor of $\frac{1}{2}$ by the potential divider consisting of R₈, R₉ and R_{V2} , but is subsequently given a gain of 2 in the summing amplifier composed of IC_{5B}, R₁₂ and R₁₃. The potentiometer R_{V2} is used to cancel the nominal offset voltage of the transducer at the lower calibration temperature. The output of the amplifier, IC_{5B} pin 7, is fed into the negative differential input of the panel meter, IN LO, IC₇ pin 30, via the other side of the low-pass filter composed of R_{14} and C_8 . This ensures that only slowly changing pressure is measured and displayed on the LCD.

The output voltage at pin 3 of the programmable current source, IC₃, has a precise and linear temperature dependence but is not zero at room temperature. The resistors R_2 and R_3 are used to modify the effective temperature coefficient of the current source by the ratio of their values so that it closely matches the nominal value of the transducer temperature coefficient. The negative potential at the output of IC4A is then used to obtain a zero potential at node A at the lower calibration temperature, which then increases linearly above this temperature. This potential is fed to one side of the two potentiometers, R_{V3} and R_{V4} and also to the inverting amplifier consisting of IC_{4B} and resistors R_{10} and R_{11} to generate an equal negative temperature dependent voltage which is then fed to the other side of the potentiometers. With IC₄ chosen for a very low temperature coefficient of offset voltage, this provides perfectly balanced positive and negative temperature dependent voltages on each side of the potentiometers. This mechanism also means that, regardless of the setting of R_{V3} and R_{V4} , the potentials at the wipers of both of these potentiometers are zero at the lower calibration temperature as required for a single cycle calibration procedure. The potential at the output of R_{V4} is added to the differential voltage of the transducer in the amplifier consisting of IC_{5B} and resistors R_{12} and R_{13} . This is then adjusted to correct the temperature coefficient of the offset voltage of the transducer at the upper calibration temperature. The potential at the output of R_{V3} is added to the nominal reference voltage of the DPM in the amplifier IC_{5A} and resistors $R_{18} - R_{21}$. This is adjusted to counteract the temperature coefficient of the transducer sensitivity at the upper calibration temperature.

5 Calibration and Testing

A prototype electronic manometer was constructed and calibrated against an RPM3 multirange pressure monitor from DH Instruments Inc. An MK53 (WTB Binder Labortechnik, GmbH) temperature controlled oven was used to vary the operating temperature. The test set up is shown in Fig.7.



Fig. 7 Calibration and test set-up

The following calibration procedure was adopted:

- (i) All potentiometers are centred initially.
- (ii) The oven temperature is brought to 20° C.
- (iii) R_{V1} is adjusted to give 0V at node A.
- (iv) An input pressure of 0mmHg is applied.
- (v) R_{V2} is adjusted until the LCD displays "000".
- (vi) The input pressure is increased to 300mmHg.
- (vii) R_{V5} is adjusted until the LCD reads "300".
- (viii) The oven temperature is then raised to 40° C.
- (ix) The input pressure is set to 0mmHg again.

- (x) R_{V4} is adjusted until the LCD reading is "000".
- (xi) The input pressure is raised to 300mmHg.
- (xii) R_{V3} is adjusted until the LCD reading is "300".

The performance of the electronic manometer was evaluated by comparing the LCD readings with those obtained from the RPM3 monitor at 10mmHg intervals in the pressure range 0-300mmHg. This comparison was made at temperatures in the range -20 °C to +60 °C in 10 °C intervals. Table 2 shows the errors recorded over the entire pressure range at each temperature. It can be seen to be zero over the entire pressure range at both calibration

temperatures and within ± 1 mmHg throughout the rest of the operating temperature range.

6 Conclusion

The electronic manometer presented has a performance and accuracy that makes it suitable for blood-pressure measurement as a replacement for mercury and aneroid gauges currently used. It operates with a high degree of accuracy over a wide temperature range and can be calibrated in a single temperature cycle. The authors are unaware of any blood-pressure monitor with this combination of

 Table 2 Results of testing of electronic manometer against reference manometer

Temperature (^o C)→									
Pressure (mmHg) ↓	-20 °C	-10 °C	0 °C	10 ^o C	20 ^o C	30 ^o C	40 ^o C	50 ^o C	60 ⁰ C
0	0	0	0	0	0	0	0	0	0
10	-1	0	0	0	0	0	0	0	-1
20	0	0	0	0	0	0	0	0	-1
30	0	0	0	0	0	0	0	0	-1
40	0	0	0	0	0	0	0	0	-1
50	0	0	0	0	0	0	0	0	-1
60	0	0	0	0	0	0	0	0	-1
70	0	0	0	0	0	0	0	0	-1
80	0	0	0	0	0	0	0	0	-1
90	0	0	0	0	0	0	0	0	-1
100	0	0	0	0	0	0	0	0	-1
110	0	0	0	0	0	0	0	0	-1
120	0	0	0	0	0	0	0	0	-1
130	0	0	0	0	0	0	0	0	-1
140	1	0	0	0	0	0	0	0	-1
150	1	1	0	0	0	0	0	0	-1
160	1	1	0	0	0	-1	0	0	-1
170	1	1	0	0	0	0	0	0	-1
180	1	1	0	0	0	-1	0	0	-1
190	1	1	0	0	0	-1	0	0	-1
200	1	1	-1	-1	0	-1	0	0	-1
210	1	1	-1	-1	0	-1	0	0	-1
220	1	1	-1	-1	0	-1	0	0	-1
230	1	1	0	-1	0	-1	0	0	-1
240	1	1	-1	-1	0	-1	0	0	-1
250	1	1	0	-1	0	-1	0	0	-1
260	1	1	0	-1	0	-1	0	0	-1
270	1	1	-1	-1	0	-1	0	0	-1
280	1	1	-1	-1	0	-1	0	0	-1
290	1	1	-1	-1	0	-1	0	0	-1
300	0	1	0	-1	0	-1	0	0	-1

accuracy and temperature range currently on the market. An initial prototype was constructed on matrix board using standard component packages and it is this version which yielded the above test results. The circuit is currently being implemented using surface-mounted technology on a doublesided printed circuit board. Some problems are being experienced with temperature drift which it is thought is due to the ceramic insulator used in most surface-mounted capacitors. Some of the critical capacitors used in the integrator section of the DPM chip may have to be replaced with polypropylene types. The electronic manometer is from a single 9V, PP3 battery. A photo of the printed circuit board prototype is shown in Fig. 8. The pressure transducer reported here can also be incorporated into blood pressure monitors which may form part of larger monitoring sytems previously reported, such as dry-electrode ECG recording equipment and SIDS risk infant monitors [12-14].



Fig. 8 Photo of the prototype electronic manometer

7 References

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