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A Wide-Range Temperature Compensated Pressure Transducer

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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 0-60^{o}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 pressure gauge or 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 the author 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 [2,3,4]. 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[7-10].

This article reports the development of an electronic pressure gauge that can be incorporated into existing sphygmomanometers to act as a 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 for determining blood pressure. This will allow the superior accuracy of electronic technology to be exploited, while at the same time addressing the reservations expressed by physicians.

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 $\pm$1mmHg is desirable. The electronic manometer presented in this paper uses a solid-state silicon pressure transducer, SX15, (SensorTechnics, GmbH), with performance characteristics as summarised in Table 1. The transducer is fabricated as a piezoresistive sensor in the form of a Wheatstone bridge, consisting of ion-implanted resistors on an integral silicon diaphragm which transform the shear stress due to applied pressure into an electrical output. The bridge is exited using an external supply voltage as shown in Fig. 1. The differential output of the sensor is given ideally by:

$$V_{OUT} = \frac{\Delta R_B}{R_B} V_B \qquad (1)$$

where ΔR_B is the fractional 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.

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:

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

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. 2. 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. Similarly, the transducer sensitivity has a

Table 1.

Performance Characteristics of SPX50 Pressure Transducer at V_B = 5V.

Parameter	*Min.*	*Typ.*	*Max.*	*Unit.*
Pressure Range:	0	-	100	kPa
Supply Current:	-	1	-	mA
Full-scale Span:	75	110	150	mV
Sensitivity:	750	1100	1500	μV/kPa
Offset Voltage:	-35	-20	0	mV
Offset T. C.:	-	+20	-	$\mu V/^0C$
Sensitivity T.C.:	-2400	-2150	-1900	$ppm/^0C$
Bridge Resistance:	-	4.65	-	kΩ
Resistance T.C.:	+690	+750	+810	$ppm/^0C$
Lin. & Hyst. Error:	-	$\pm$0.2	$\pm$0.5	%FS

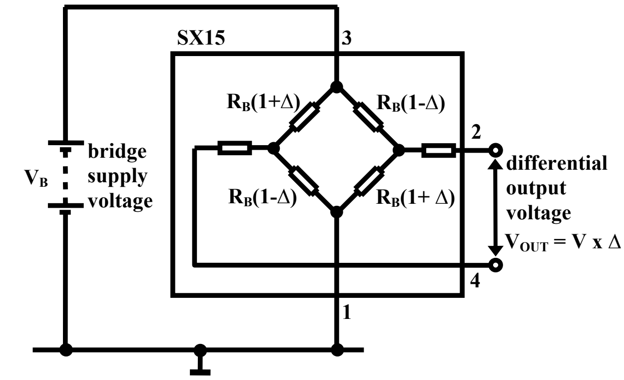

Fig. 1 *The pressure transducer bridge arrangement*

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.

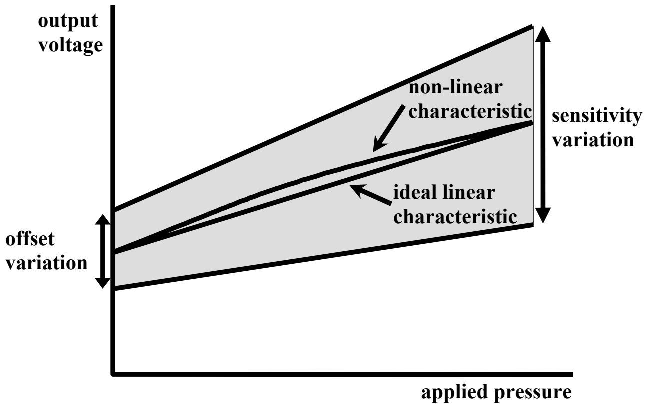

Fig. 2 *Typical pressure transducer characteristics*

3 Design Considerations

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

$$V_{OUT} = S_0[1+\alpha(T-T_0)].V_{B0}.p + V_{OS0}[1+\beta(T-T_0)] \qquad (3)$$

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.

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. The transducer output will normally be amplified to raise the voltage to a suitable level for display purposes. Variations in the sensitivity can be corrected by making the amplifier gain 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 voltage to change with temperature in a direction opposite to that of the sensitivity, so that the resulting output voltage vs. pressure after conditioning becomes independent of temperature. In this case, the output voltage from the signal conditioning amplifier can be described as:

$$V_{OUT} = GS_0[1+\alpha(T-T_0)]V_{B0}[1+\gamma(T-T_0)]p + V_{OS0}[1+\beta(T-T_0)] + V_{OC0}[1+\delta(T-T_0)] \quad (4)$$

where:
V_{OC0} is offset cancellation voltage at temperature T_0,
δ is the temperature coefficient of the cancellation voltage,
γ is the temperature coefficient of the bridge voltage and the other parameters are as above.

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

$$V_{OUT} = GS_0V_{B0}p \quad (5)$$

This is accomplished by making $V_{OC0} = -V_{OS0}$, $\delta = \beta$ and $\gamma = -\alpha$. If these conditions are substituted into equation 4, the resulting output after signal conditioning is:

$$V_{OUT} = GS_0V_{B0}p[1+\gamma\alpha(T-T_0)^2] = GS_0V_{B0}p(1-\alpha^2\Delta T^2) \quad (6)$$

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 as well as the extent of the operating temperature range. Table1 gives the highest value of α as -2400 ppm/^{o}C for the transducer. If the maximum temperature deviation from T_0 is taken as 25^{o}C, then the worst case error will be $\pm$0.36% which at full scale span is marginally above $\pm$1mmHg. The combined worst-case hysteresis and non-linearity error is given in Table 1 as $\pm$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 be maintained within $\pm$1mmHg ($\pm$0.13kPa).

Temperature compensation circuits pose additional problems in the calibration procedure. Calibration for a limited temperature range, over which temperature coefficients can be assumed constant, 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 temperature, commonly room temperature or 25^{o}C. Consequently, calibration becomes an iterative procedure whereby several iterations of adjustment are necessary to obtain an acceptable degree of accuracy. Fig. 3 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), the latter when projected backwards on the temperature scale having a zero output at some negative value of temperature, typically absolute zero in Kelvin. 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 as shown in Fig. 3(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. 3(b). This however, disturbs the match at the lower point so that an error is reintroduced at temperature T_o. This requires a second adjustment at the lower temperature, T_o. The second adjustment at temperature T_o then disturbs the match at the upper point as shown in Fig. 3(c). A second adjustment at temperature T_1 restores the match at the upper point but reintroduces an error at the lower point as can be seen in Fig. 3(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. A similar problem arises in the

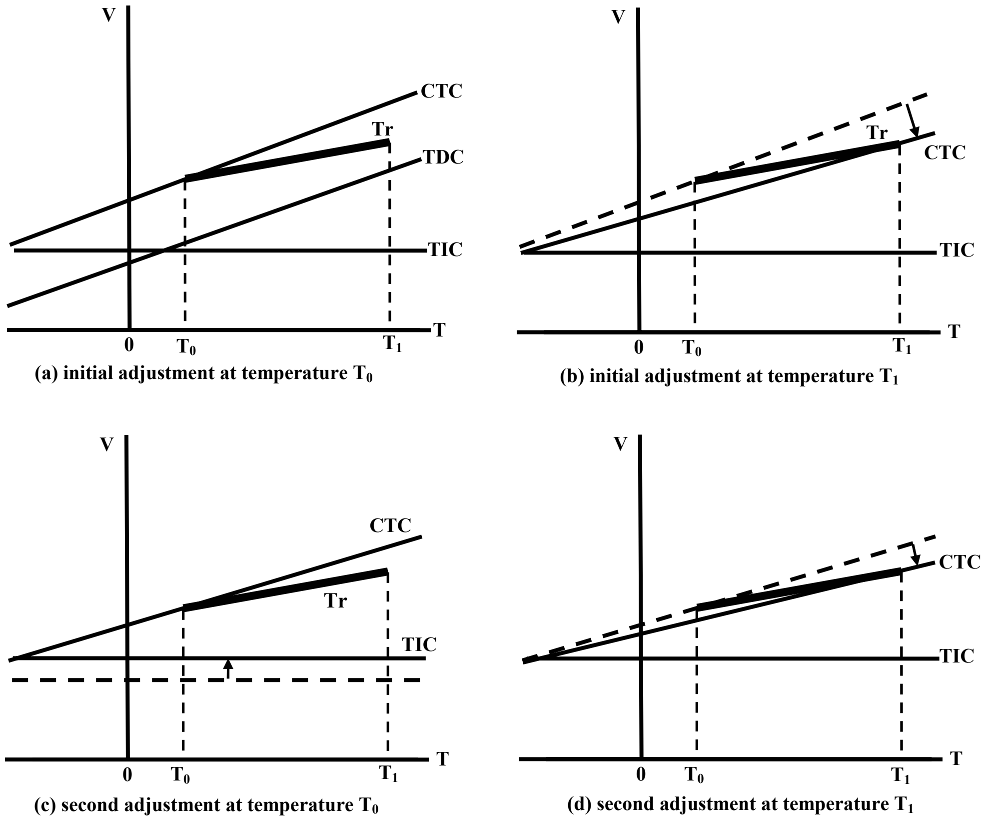

Fig. 3 *Adjustment of the temperature compensation mechanism for the transducer offset voltage*
TIC: temperature independent component, TDC: temperature dependent component,
CTC: combined temperature compensation, Tr:transducer characteristic.

compensation of the temperature dependence of the transducer sensitivity.

On the other hand, a temperature sensor such as the LM35 from National Semiconductor Corp. provides an output voltage which is a linear function of temperature and also has the advantage of zero output voltage at a temperature of 0^{o}C. In this case a single temperature cycle calibration is possible as indicated in Fig. 4 if the lower calibration temperature is chosen as 0^{o}C. Firstly, the temperature independent voltage is adjusted at 0^{o}C so that the combined compensating voltage matches the transducer characteristic as seen in Fig. 4(a). Following this, the slope of the temperature dependent component is adjusted to give a match with the transducer characteristic at the higher calibration temperature as seen in Fig. 4(b). This, however, does not disturb the match at the lower calibration point of 0^{o}C and so the combined compensation voltage matches the transducer offset characteristic over the full range, provided that it is linear over the range in question. If this is the case, no further iteration is necessary and calibration is complete.

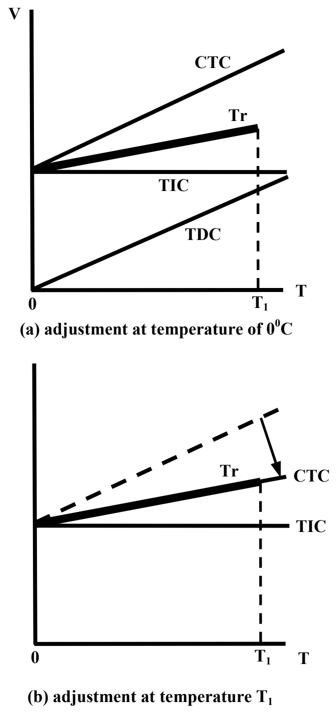

Fig. 4 *Single Cycle Calibration*

4 Circuit Implementation

The heart of the electronic manometer is the digital panel meter (DPM), IC_5, a MAX138 from Maxim Inc., which is a differential-input, ratiometric DPM, having a very high input common-mode rejection ratio as well as an on-chip positive-to-negative supply converter. It provides a direct drive facility for a 3½ digit liquid crystal display (LCD). The numerical output displayed on the LCD is given as:

$$N = 1000 \text{ x } \frac{V_{IN\,HI} - V_{IN\,LO}}{V_{REF\,HI} - V_{REF\,LO}} \qquad (9)$$

The reference voltage is obtained via a potential divider placed across an internal precision voltage reference which exists between the supply rail and the analogue common pin on the DPM. The other ancillary components connected to IC_5 are chosen in accordance with the manufacturer's recommendations for optimum performance.

The circuit is powered from a battery which feeds a 5V voltage regulator, IC_1, with a low dropout voltage and a battery low-voltage monitor. Positive and negative temperature-independent voltages are generated using reference diodes ZD_1 and ZD_2, which have near-zero temperature coefficients, and the resistor chain R_1 – R_5. The temperature sensor, IC_3, provides an output voltage having a slope of 10mV/^{o}C. This output is fed to a potential divider chain, R_6 – R_9 which generates two temperature dependent output voltages, one of slope 2.5mV/^{o}C and the other of slope 110µV/^{o}C.

The higher temperature dependent output voltage at R_{V2} is fed into one input of the summing amplifier composed of IC_{4D}, R_{10} and R_{11} and combined with the temperature independent voltage of -1.25V from reference diode ZD_2. This provides the bridge voltage, V_B, which feeds the pressure transducer with a nominal voltage of 3.84V and a variable positive temperature coefficient which can be adjusted via R_{V2} to counteract the negative temperature coefficient of transducer sensitivity. The lower temperature dependent output voltage at the top of resistor, R_9, is fed to one side of the potentiometer, R_{V3}, via resistor, R_{14}, and also into the inverting amplifier composed of IC_{4A}, R_{15} and R_{16} where it is inverted and fed to the other side of potentiometer, R_{V3}, via resistor, R_{17}. The output from potentiometer R_{V3} can therefore be adjusted to obtain a positive or negative temperature coefficient to compensate the temperature dependence of the transducer offset voltage in either direction. This output voltage is combined with the temperature independent voltage from the potentiometer, R_{V1}, which is adjusted to cancel the nominal offset voltage of the transducer, in the summing amplifier consisting of IC_{4B}, R_{12} and R_{13}.

The output voltage from the negative side of the transducer is scaled by a factor of ½ by the potential divider consisting of R_{18}, R_{19} and R_{20}, chosen to allow for loading effects, but is subsequently given a gain of 2 and added to the combined offset compensating voltage in a final summing amplifier composed of IC_{4C}, R_{21} and R_{22}. The output of this amplifier is fed into the negative differential input of the panel meter, IC_5 pin30, via a low-pass filter composed of R_{26} and C_8. The positive output of the transducer is fed via the low pass filter comprising of R_{25} and C_8 to the positive differential input pin of the panel meter, IC_5 pin31. The variation in the full-scale span output at 25^{o}C is counteracted by adjustment of the panel meter reference voltage at IC_5 pin36, supplied via the resistors R_{23}, R_{24} and potentiometer, R_{V4}, in conjunction with the internal band-gap voltage reference of the DPM, IC_5. The negative reference input pin, IC_5 pin35, is connected to the analogue common input, IC_5 pin32.

5 Calibration and Testing

A prototype electronic manometer was constructed and calibrated against an RPM3 multi-range pressure monitor from DH Instruments Inc. An MK53 (WTB Binder Labortechnik, GmbH) temperature controlled oven was used to vary the operating temperature. The following calibration procedure was adopted:

(i) All potentiometers are centred initially.
(ii) The oven temperature is brought to 0^{o}C.
(iii) At applied pressure of 0mmHg, potentiometer, R_{V1}, is adjusted until the LCD displays "000".
(iv) The input pressure to the transducer is then raised to 300mmHg.
(v) Potentiometer, R_{V4}, is adjusted until the LCD displays a reading of "300".
(vi) The oven temperature is then raised to 40^{o}C.
(vii)With zero input pressure applied, potentiometer, R_{V3}, is adjusted until the LCD reading is "000".
(viii) The input pressure is raised to 300mmHg.
(viii) R_{V2} 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 between 0^{o}C and 60^{o}C in 10^{o}C intervals. Errors of less than $\pm$0.5 mmHg did not register on the display as it had a digital resolution of 1mmHg. Zero error was recorded over the entire scale for temperatures between 0^{o}C and 50^{o}C. Only an error of -1mmHg

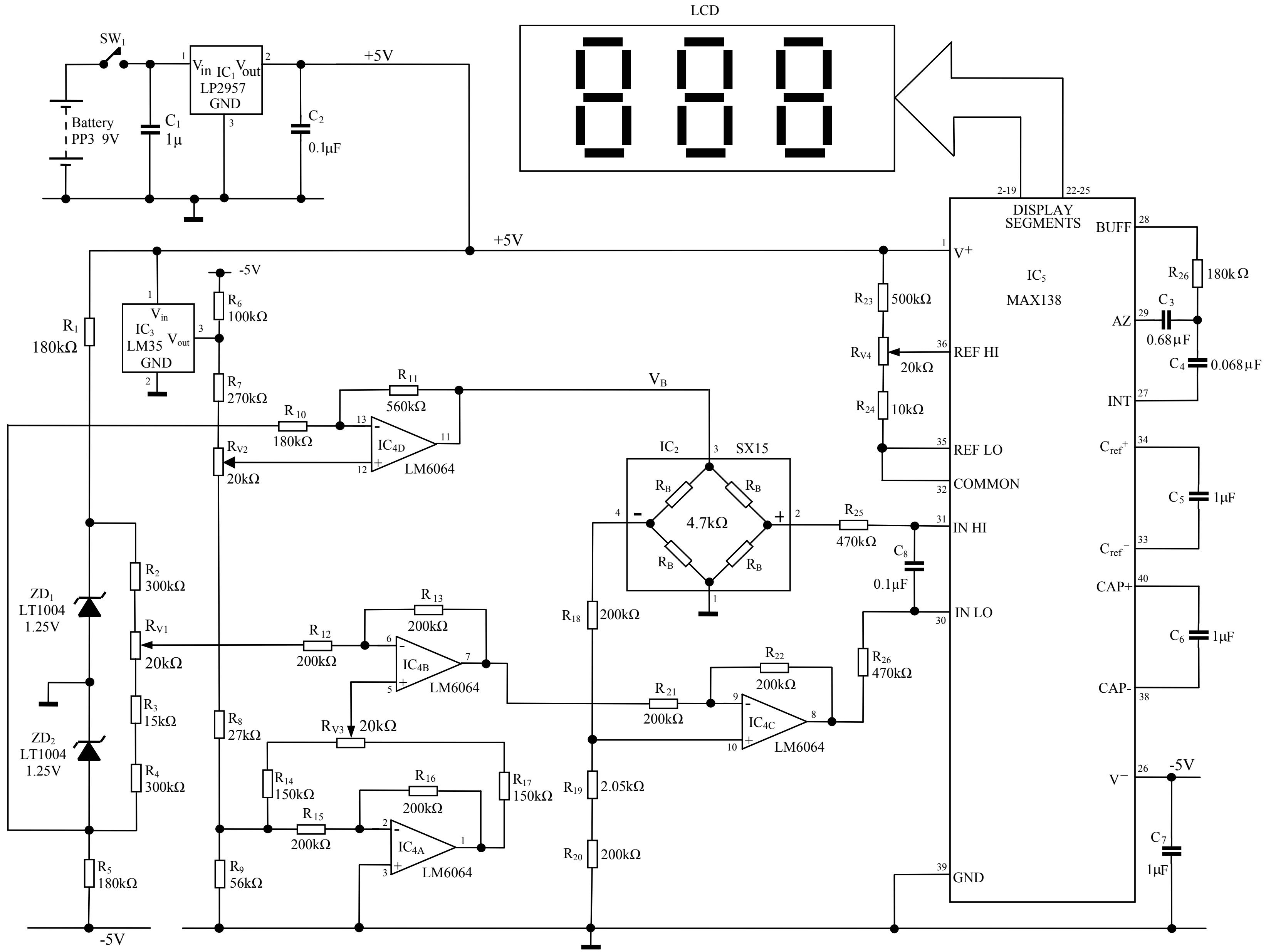

Fig. 5 *Schematic Diagram of Electronic Pressure Transducer*

was recorded for pressures above 260mmHg at 60^{o}C.

6 Conclusion

The electronic manometer presented has a performance and accuracy that makes it suitable for blood-pressure measurement and an excellent replacement for mercury and aneroid gauges currently used for this purpose. It operates with a high degree of accuracy, with measurement errors of less than $\pm$1mmHg over a wide temperature range of 0 – 60^{o}C, which will cater for the measurement of blood-pressure under any practical conditions worldwide in which it is likely to be necessary. The authors are unaware of any blood-pressure monitor with this combination accuracy and temperature range currently on the market. The prototype was constructed on matrix board using standard dual-in-line component packages, but could readily be implemented in surface-mount technology for miniaturisation, should this be desireable. It is powered from a 9V, PP3 battery.

7 References

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