Nigerian Journal of Technology (NIJOTECH)
Vol. 32. No. 2. July 2013, pp. 217-224

University of Nigeria, Nsukka, ISSN 1115-8443
www.nijotech.com

REDUCTION OF TEMPERATURE DEPENDENT DRIFT IN ON-LINE WEAR DEBRIS HALL EFFECT SENSOR

+E. B. Edet, K. M. Udofia, P. M. Asuquo
DEPARTMENT OF ELECTRICAL ENGINEERING, UNIVERSITY OF UYO, UYO, NIGERIA
+Corresponding author E-mail: emmanueledet@uniuyo.edu.ng

Abstract
In this work, efforts have been made towards finding suitable techniques of minimizingoutput drifts in the operation of an online wear debris Hall Effect sensor. Hall chip (with an ALNICO permanent magnet) output fluctuates at a rate of about 1mV per a degree change in Celsius. This was observed whenHall sensor chip (HAL815) was used with an ALNICO permanent magnet to build a wear debris sensor for machine condition monitoring. Other chips have been tested such as HAL825 but the variation was still found to be within that range under similar conditions. Tests carried out in this work indicated that any kind of noise reduction technique must have some form of impact on the stability of the magnet since it has been found to be a major contributor to the drifts in the system due to hysteresis over temperature fluctuation. All the tests were carried out by placing 80mg wear debris on the sensor head in an environmental chamber connected to a LABVIEW MMI (man-machine interface) and LABVIEW was used for all simulations and data acquisition. Several techniques of strengthening signal to noise ratio as well as noise reduction schemes have been investigated such as: Calculated output correction, environmental monitoring/control, use of low noise electronic components and method of opposing environmental input (differential method). Opposing input (differential) technique was found to be the most stable drift correcting method on this device as drift was reduced to about 0.1%fsd over temperature variation from 10˚C - 60˚C thus improving the stability of operation of the sensor.

Keywords: Hall Effect, sensor, noise reduction, hysteresis, temperature dependent drift, stability, full scale deflection, LABVIEW

1. Introduction

In many silicon Hall effect sensors, there are a number of manufacturing imperfections such as non-linearities, cross sensitivities, additive and interfering noise inputs [1].These limit their engineering applications such as machine condition monitoring. One machine condition monitoring technique where Hall Effect sensor is applied is ferrous wear debris sensing in lubrication oil for machines and electromechanical plants [2, 4]. The device is supposed to give a trend of an output that corresponds to the level of wear and tear of mechanical part. Therefore, there is a high demand for reliability and repeatability of the device under all working conditions. Consequently, the output formats whether analog or digital, must conform to available standards and the characteristics must be identical.

The primary sensing element in such a device is a Hall effect chip which works based on electromagnetic principle. When a magnetic field is applied to a current carrying conductor at right angle, as illustrated in figure 1, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. A small measurable voltage appears across the current carrying plate and this small transverse voltage is termed Hall voltage, named after Edwin Hall who discovered it in 1879. If the polarity of the magnetic field is reversed, it is always observed that the polarity of the hall voltage changes accordingly [3, 5]. It is illustrated below:

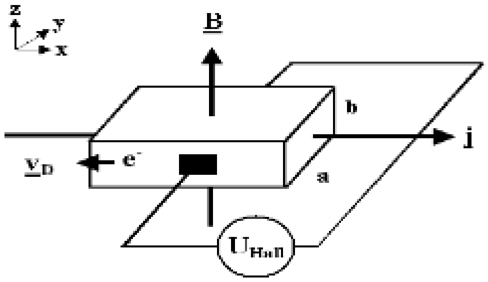

Figure 1: Hall principle

Earlier experiments carried out by some notable scientists such as Edwin and Faraday in magnetism and electromagnetism produced useful relationships between quantities like induced voltage, electric field and the strength of the applied magnetic field. This relationship is expressed in the equation below:

$$E = (qv \times B) \quad (1)$$

Where 'E' represents the electric field; q – the charge; v – the velocity of charge; and B – the magnetic field.

The resultant force (F) on the charged particles due to the electric and magnetic field is given by the Lorentz force equation given below:

$$F = qE + qv \times B \quad (2)$$

In a Hall transducer, the velocity of charge is in one direction along the length of the device as shown in Figure 1. This implies that the Hall Effect transducer will be sensitive only to one component of the magnetic field. Therefore, Hall Effect device is orientation sensitive. For instance, the hall chip used in this work is sensitive to magnetic field applied along a single axis and is substantially insensitive to components on the other two remaining axes [2,5]. In the hall device, electric field is set up because, as the magnetic field forces the charge carriers to one side of the hall transducer, excess concentration of charges on one side and a consequent depletion on the other side gives rise to an electric field across the transducer. The field causes the charges to try to redistribute themselves more evenly and it also gives rise to a measureable voltage across the hall plate [2]. The hall voltage equation in a semiconductor hall sensor can be modelled as follows:

$$V = \frac{IB}{qNd} \quad (3)$$

Where: I = Current
B = Magnetic field
q = Charge on an electron
N = Carrier density
d = Thickness of doped material.

Equilibrium is reached when the magnetic force pushing the charge carriers aside is balanced out by the electric force trying to push them back towards the middle [5] .This is utilized in designing a sensor for machine condition monitoring. In this application, Hall Sensor is used in an intelligent circuit designed to capture the amount of wear debris in circulating lubrication oil. The hall voltage is linearly dependent on the magnetic field strength. Consequently, any change in magnetic flux due to ferrous wear debris deposition can be acquired as a voltage signal. This process of conversion of signal from one energy form to another energy form (electrical energy) of similar variations is termed transduction. Therefore, deposition of wear debris on the hall probe is measureable by the process of transduction. This is the data acquisition section of the device. The hall chip is therefore called the transducer and this term will be widely used in this work to refer to the hall integrated circuit chip. When the lubrication oil flows across the sensor head, ferrous wear debris in the lubrication oil is attracted by the magnet towards the hall probe. This results in magnetic flux change which is converted to a small hall voltage by the transducer. This hall voltage output depends on the amount of wear debris deposited on the sensing head.

As debris accumulates, the magnetic circuit will eventually saturate. This will be detected by the input value of the microprocessor and a control signal is passed on to an electric motor which initiates the flushing cycle and the process is repeated.

The sensor's head assembly consists of hall sensor chip, temperature sensor chip installed within the cavity of the permanent magnet and a holding material to keep the sensor in a single and most sensitive position. The temperature sensor is there to detect instantaneous values of environmental temperature for reasonable compensation in the output of the device. However, there is a non-ferrous foil that surrounds the head in order to facilitate debris flushing off the magnet. The thin foil is made up of a brass layer. The sensor is installed online in the plant and as lubrication oil flows across the sensor head, information about wear debris content can be captured which reflects the health of the machine. The operation of this Hall device application is as illustrated in Figure 2. A Silicon Hall effect sensor used in the monitoring wear debris in machine's lubrication oil is ideally supposed to sense only the level of wear debris by measuring the induced hall voltage across the current carrying conductor located in a magnetic field. Practically, this is not true as voltage drift is experienced even when there is a fixed amount of wear debris, thus, may result in false alarm of wear and tear in the monitored machine parts.

2. Problem Statement

The voltage output from Hall Effect Sensor employed as a primary transducer in wear debris monitoring was found to drift with temperature as shown below in figure 3 when viewed on the LABVIEW HMI.

Using LABVIEW based HMI (Human Machine Interface), 80mg of wear debris was fixed on a Hall Effect sensor's head, and the output was monitored in a Controlled-Environment-Chamber (CEC).

Ideally, the output is expected to be a stable voltage output of about 2.5V which is converted to discrete signal – 600steps. This is expected to be so because a steady amount of wear debris (80mg) was fixed on the sensor. However, this was not the case when monitored via the human machine's interface. When the sensor's output deviation was plotted against temperature, the deviation was found to be temperature dependent. The higher the temperature, the higher the drift or deviation as shown below in figure 4.

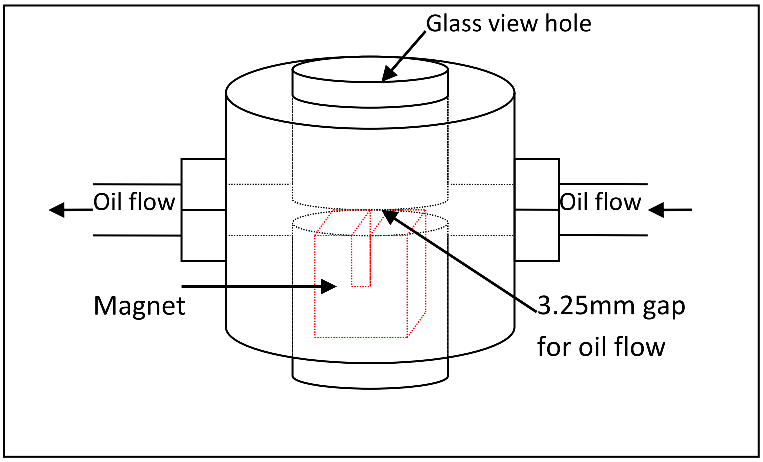

Figure 2: Diagram of the sensor showing the inner section of manifold where the particles are captured .

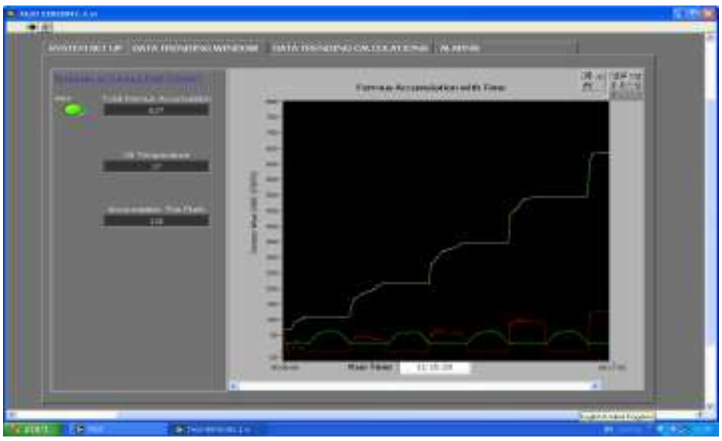

Figure 3: Practical output trend with oil temperature variation in a controlled environmental chamber.

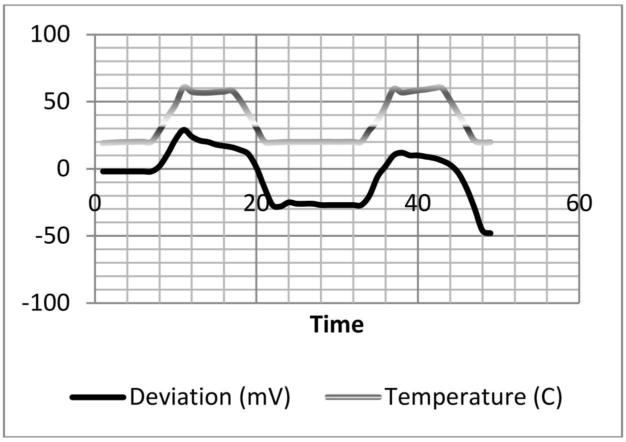

Figure 4: Sensor output trend with temperature

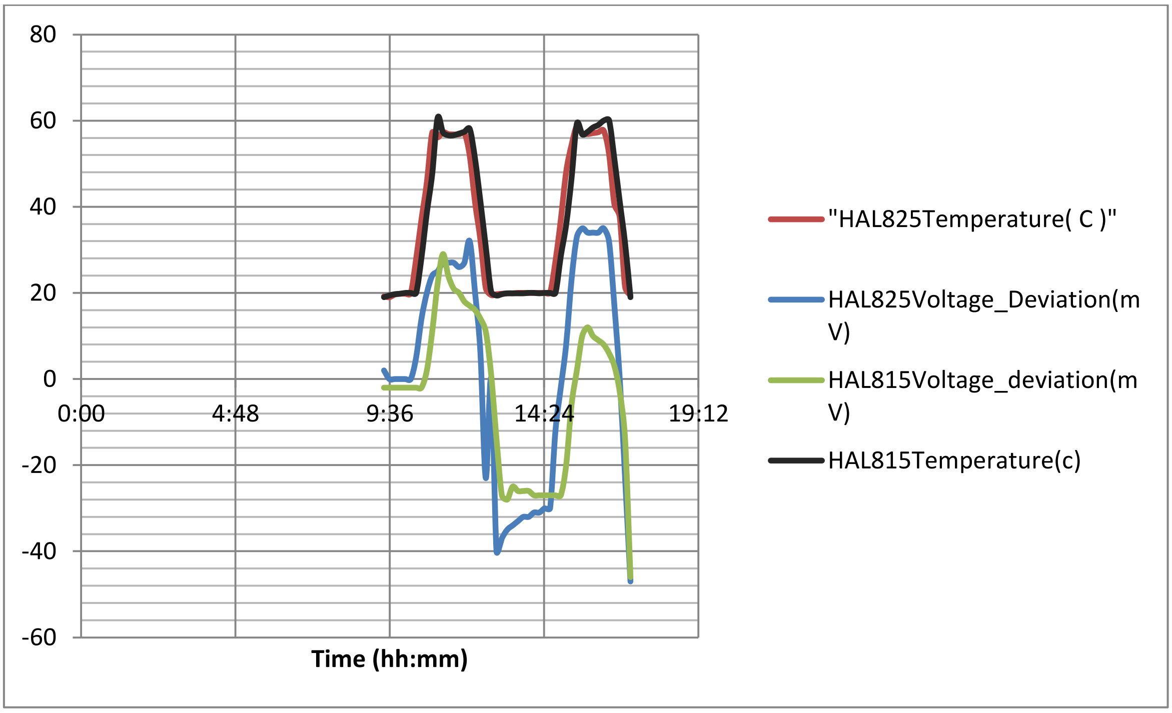

Figure 5: Variation of HAL825 and HAL815 output with temperature

A confirmation test with another sensor head (HAL825) indicates the same problem as in Fig. 5. In tabular form, the result of the HAL 815 output tests with temperature is presented as follows.

Thus, there is a high probability of false alarm as a result of stray and misleading information about the health of the monitored piece of machinery if the sensor is used directly without any form of noise voltage compensation.

3. Sources of Temperature Rise and Fluctuation in the Design

Although many causes such as stress, manufacturing imperfections and changes in temperature are associated with Hall Sensor's output drift, change in temperature is the most pronounced.

When a machine is put on and left to run over a period of time, it heats up especially if there are moving parts. This heating is transferred to the lubrication oil that circulates around the piece of machinery. Therefore when the heated lubrication oil flows through the sensing head of the equipment, the wear detection is distorted by temperature rise as the primary sensing element (hall sensor) is affected. Secondly, there are other sources of heat in a machine such as presence of faulty component, overloading or external heat and all these conditions can cause an unexpected increase in the temperature of an electromechanical plant such as a wind turbine.

In addition, there is a stress drift due to packaging of the chip during fabrication and it is another source of noise in a hall sensor. However, the permanent magnet is the part that is mostly showing distorted operation due to increase in temperature. The hall chip has been developed over the years in order to have a product with stable output even in adverse environmental conditions such as temperature fluctuation though the result is still not satisfactory thereby making Hall sensing inferior to other sensing techniques like inductive sensing.

4. Methods of drift reduction

4.1 Offset Reduction by Spinning Current Method

In this method of reducing offset, during hall sensor chip fabrication, consecutive current injections are introduced in different orientations of a symmetric hall plate and the average of the measurement results is the output signal [7,8]. It relies on the different symmetries of the hall effect and various transduction effects which contributes to the offset in order to average the results of several consecutive hall measurements with different orientations in the crystal plane [8].

One way of carrying out this current injection is by utilizing different Hall material orientations. These currents are injected at the same time at different points on the outer and inner boundaries of the hall sample. In this way, the magnetic field sensitive signal along with a separate stress sensitive signal can be measured simultaneously at another pair of voltage points [6].

Without using a suitable offset compensation technique such as this current spinning method, it is important to realise that stress drifts due to the plastic encapsulation of the chip during fabrication will cause voltage drifts of the offset through transductive effects like the piezoresistive effects on the chip. This causes signal instability as a result of the variable stress in the hall chip created during packaging. A variable stress in the sensor chip transform itself via the piezo-resistive and piezohall effects into the sensor signal parameter variations [9]. This offset will inevitably be carried over into any eventual product where the chip is applied. Muller proved experimentally that with the spinning current method, a very small residual offset well below 100μT is achievable if the current is limited so that the non-linear contribution to the input resistance remained below 10%. This was experimentally proven by determining the residual offsets of four spinning current hall plates based on four orientations [10]. In many CMOS (Complementary metal oxide semiconductor) hall circuits, the method of spinning current allows offsets to be reduced to 0.5mT although it can be much better.

In addition to reducing offset, the spinning current method has been proven to completely eradicate the influence of flicker noise (1/f) in a hall element. This is achieved by using a hall element with a chopped integrated amplifier. In many commercially available CMOS, this technique is applied to virtually eliminate flicker noise. Moreover, by using an array of four hall elements, the chances of a reappearance of the noise at an internal switching frequency is brought low due to the realisation of a very low noise density [6,9]. However, this method will not have any effect on magnetically induced variations such as hysteresis. It is only effective in reducing the noise effects due to the hall sensor chip.

4.2 Autocalibration of silicon Hall chip

With the implementation of Autocalibration in the sensor chip design, problems arising due to unstable sensitivity are solved. Furthermore, Autocalibration eliminates the need for calibration during product manufacturing or during the lifetime of the sensor [10].

In this method, an on-chip actuator, which generates a reference signal, is used to correct the hall sensor's changing sensitivity. It is applicable in the design of smart hall sensors. This is because, in a smart sensor, there is some form of on-chip signal processing and intelligence. The principle of autocalibration involves the addition of an element that is capable of stimulating the sensor with a well defined reference signal. Consequently, the characteristics of the sensing device can be computed by an on-chip processor [6]. In other words, the hall chip contains both a sensing element and an actuator on the same chip (sensactor) in order to carry out autocalibration as shown in the following diagram:

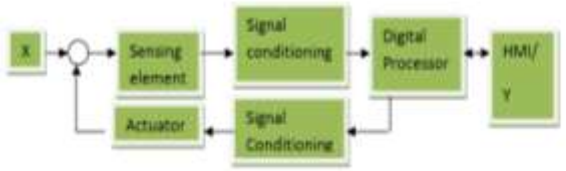

Figure 6: Block diagram showing the implementation of autocalibration on a single hall chip with input variable(X) and output variable Y.

The sensactor operates in two modes namely: measurement mode and calibration mode. In measurement mode, the output signal of the sensing element is conditioned and converted to a digital signal before it is passed to a microprocessor unit. In the microprocessor unit, the signal is transformed to a calibrated output signal using the most recent calibration curve stored in memory [11]. Thereafter, the microprocessor changes to calibration mode. The actuator then sends a set of reference values of the physical input quantity to the sensing element. In subsequent measurements, the sensing element produces a set of signals from which the microprocessor can compute a new calibration curve and the process is repeated.
The result of an autocalibrated system is that a standard output which is already calibrated is produced and it is independent of internal differences caused by manufacturing irregularities. Another benefit of autocalibration is the self-test function. If the output signal does not meet the expected value by the user, a complete failure of the system is detected. In this way, the self-test function of autocalibration prevents the delivery of erroneous output values. Again, this method does not affect noise inputs related to the magnet.

4.3 Magnetic flux concentrators

Another optional technique of coping with voltage offset and noise in hall sensor chip is by the use of integrated magnetic flux concentrators. The flux concentrators function by converting magnetic field parallel with the chip surface into a magnetic field perpendicular to the chip surface [3,8]. Thus, it amplifies the useful magnetic signal sensed by the hall element.
This is achieved by placing two pairs of hall elements below the flux concentrators on the chip in order to produce a hall sensor system with magnetic gain. The result is that a higher magnetic sensitivity, lower equivalent magnetic offset and lower equivalent magnetic noise are achieved compared to conventional hall effect sensors [12]. However, better performance has been proven experimentally with the use of spinning current method.

4.4 Proposed Method of Opposing Inputs

This is a differential method of cancelling out noise or signal impairment in practical systems. In this work, a second (calibrated) Hall sensor is introduced in the same system but without the wear debris deposition (dummy with respect to debris deposition) in order to cater for temperature compensation and any other undesired effect. When the two sensor heads are exposed to the same environment (oil temperature) but with the first sensor (A) sensitive to the oil with the debris before filtration while sensor B reflects only the oil temperature, the output of the entire sensing subsystem is obtained via a differential amplifier with excellent CMRR (Common Mode Rejection Ratio).The resultant output signal will effectively represent the effects of wear debris deposition only.This is illustrated in figure 7. In this way the combined impact of temperature deviations on both the magnet and the sensor are highly minimised. One of the problems associated with the implementation of this method is the fact that two sensor head assemblies will be required where one is installed before the filter while the second should be installed down the line after the filter. Thus, size becomes a limitation. Since there are other methods of condition monitoring, it is important to take decision on the design with the final consumer in mind and the commercial aspect of the entire venture. A second limitation is the challenge of obtaining two similar magnets with identical field. Due to hysteresis, there is a lack of repeatability when magnets are used in measurement circuits especially when temperatures are actually changing based on the environment. However, when the two sensor heads are connected via an excellent operational amplifier, the effects of minute field disparity between the two magnets are negligible. For these reasons, this differential method gives a realistic design solution.

5. Results

The result of test carried out while using two sensor heads (with one of the sensor strictly for temperature compensation and the other sensor carrying 80mg wear deposition) is as shown in figure 8.

Since the two senor heads are precalibrated and installed in the same oil temperature environment, effects of temperature and magnetic hysteresis were subdued. Results of tests carried out by placing fixed 80mg ferrous debris on the sensor head in a controlled temperature chamber show a stable output as shown above even when temperature was systematically varied from 10C to 60C.The output was 2.51mV reflecting wear debris deposition of 80mg. This signal can be amplified and processed to give a digital trend reflecting the health of the machinery at the control panel.

6. Discussion of Results and Recommendations

In this paper, several ways of reducing Hall sensor's output drift has been presented.

With the implementation of calculated output compensation using microprocessor-based system, there will still be output drift due to hysteresis of the magnetic field over any given temperature range. For instance, the calculated value of noise over 20°C to 80°C at one time has been found to be insufficient at another instance due to hysteresis as the magnet heats up and cooled down. This introduces a problem of repeatability. Temperature monitoring and application of low noise devices are actually helpful but insufficient. In conclusion, a method of opposing environmental inputs was proposed and found to be the most effective drift reduction technique due to the differential method of obtaining signal output. Thus, the signal measurement under this method is differential mode instead of single point measurement from one sensor. Therefore, by using a second Hall sensing head for temperature compensation, we can obtain a stable output over temperature range of 10C to 60C with drift reduced to less than 0.05% thus improving the accuracy of the Hall Effect sensor.

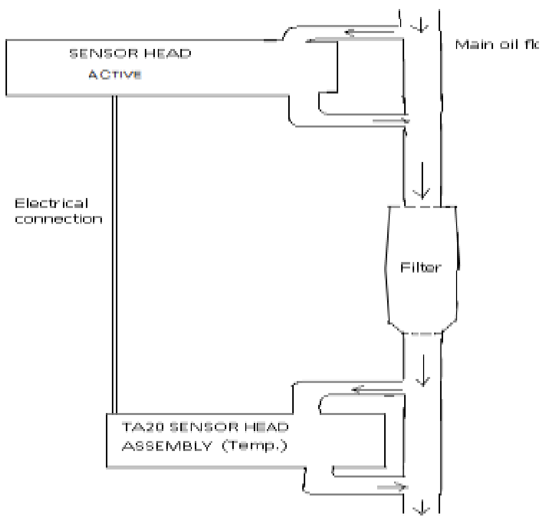

Figure 7: Noise reduction technique by method of opposing inputs.

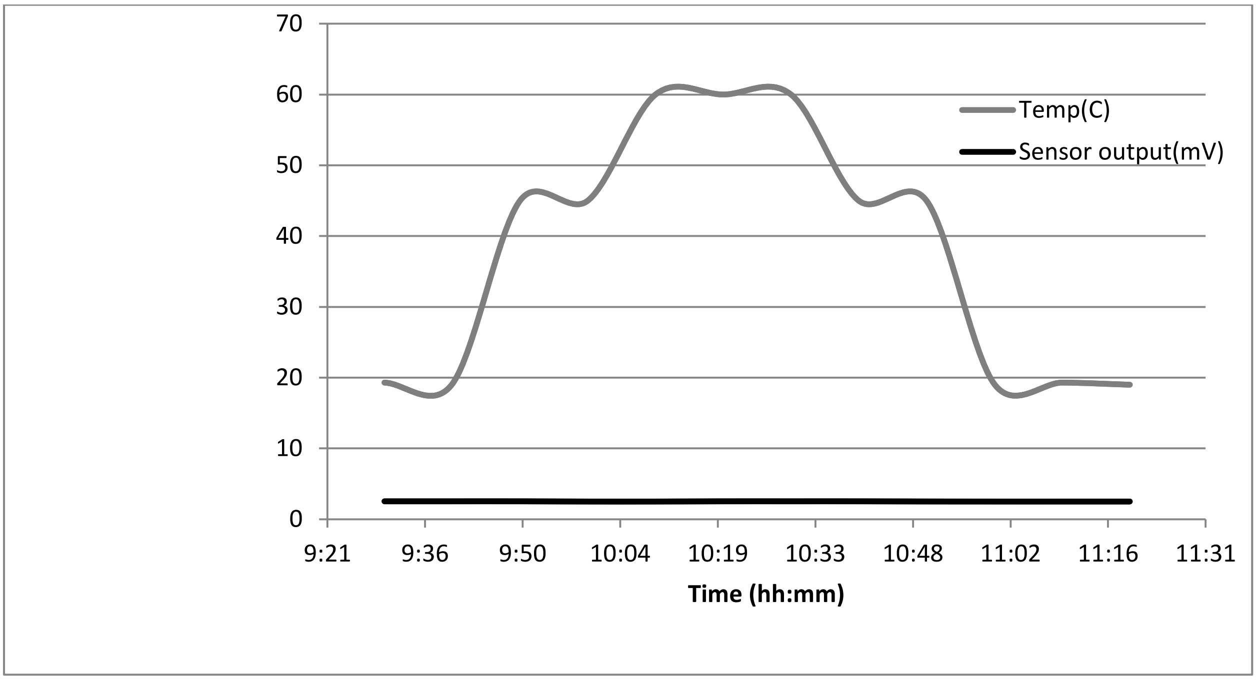

Figure 8: Output of the sensor after recommended compensation for temperature based drifts

References

[1] Bentley, J. *Principles of Measurement Systems* 5th ed. Essex: Pearson Education Limited, 2009, pp. 3-9, ISBN 978-0-13-043028-1

[2] Blanchard, H., Highly sensitive Hall sensor in CMOS technology, *Sensors and Actuators,* Vol. 82 (1), 2000 , pp. 144 - 148. ISSN 09244247

[3] Bolton, W. *Industrial Control and Automation* [Online] London: University press. 2005, Available at: Glasgow Caledonian University Catalogue http://www.gcal.ac.uk/library

[4] Chiou, Y., Lee, R., Tsai, C. On-line Hall-effect device for monitoring wear particle in oils, *Wear*, Vol. 223(2), 2000, pp. 44-49, ISSN 00431648.

[5] Edward, R. *Hall-effect sensors theory and applications* 2nd ed.2006, Amsterdam: Boston.

[6] Hunt, T., Evans, J. *Machine and system condition monitoring series* 2nd ed. Oxford: Coxmoor Publishers,2004, ISBN 1 901892 050

[7] Manic, D. Temperature cross-sensitivity of Hall plate in submicron CMOS technology, *Sensors and Actuators,* Vol. 85 (1), 2000, pp. 244 - 248. ISSN 09244247

[8] Micronas *Micronas Semiconductor Technologies*, 2008, Freiburg, Germany http://www.micronas.com [Accessed 30 June 2012]

[9] Muller, C., *et al.* Offset reduction in silicon Hall sensors, *Sensors and Actuators,* Vol. 81 (1), 2000, pp. 18 - 22. ISSN 09244247

[10] Pallas-Areny, R., Webster, J. *Sensors and signal conditioning* 2nd ed. 2000, New York: John Wiley Publishers.

[11] Popovic, R., Randjelovic, Z., Manic, D. Integrated Hall-effect magnetic sensors, *Sensors and Actuators,* Vol. 91 (1), 2001, pp. 46-50.ISSN 09244247

[12] Trontelj, J. Optimization of integrated magnetic sensor by mixed signal processing, in: *Proceedings of the 16th IEEE Instrumentation and Measurement Technology Conference (IMTC99)* 1999, pp. 299-302.