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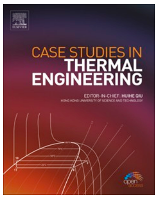

Experimental thermal characterisation of an ironless inductive position sensor

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ABSTRACT

This article reports an experimental study performed on the ironless inductive position sensor to understand the relationship between changes in the surrounding temperature and position reading of the novel linear position sensor. The measured variation of the basic electrical components with temperature is presented and shows that the position drift of the sensor varies with the state of the sensor. The states include the moving coil position, and the frequency of operation. The results also reveal that the resistance and inductance changes happen in all the coils. Furthermore, the results show that when subjected to an even temperature change, the moving coil contributes to the highest change. In addition, uneven thermal distribution along the body of the sensor leads to high sensitivity from the sense coils. The results also indicate that the inductance change is small and leads to a small position change.

1. Introduction

Safety critical applications in harsh environment require high accuracy, repeatability, and low drift. The Ironless Inductive Position Sensor (I2PS) is an air-cored, high-precision linear position sensor, which is designed to be immune from radiation and external magnetic fields. It is thus used as an alternative to the Linear Variable Differential Transformer (LVDT), in places characterised by magnetic environments. Spezia et al. in Ref. [1] explains the susceptibility and the position error noted when the LVDT is close to magnetic interference. These two sensors are used to determine the position of the European Organization for Nuclear Research (CERN) Large Hadron Collider (LHC) collimator's jaws with respect to the particle beam [2–4]. In brief, a collimator cleans the beam halo by physically blocking the particles using its 1 m to 2 m long jaws. Therefore, since the jaw position with respect to the beam is critical for the safe operation, the jaws have to be measured with a 20 μm maximum target position uncertainty. Furthermore, due to radiation presence in CERN accelerators, the I2PS has been designed to have no on-board electronics; the raw signal has to be carried through long cable lengths. The complete design procedure and model of the I2PS is described in Ref. [5]. During the design phase, the thermal sensitivity of the sensor is considered and a temperature compensation algorithm is conceived to stabilise the sensor's position drifts. The lab experiments performed showed promising results but from the I2PS installed in some of the LHC collimators, it is noted that the sensor's overall performance, although still good, exhibits temperature drifts that can be attributed to day-night changes and monthly temperature drifts in the LHC tunnel. Moreover, the aforementioned day-night and monthly position drifts are not constant for temperatures recorded on different months for the same sensor. Furthermore, the readings from one I2PS vary in magnitude and duration with respect to other I2PS installed but operated at other positions hence giving an impression of

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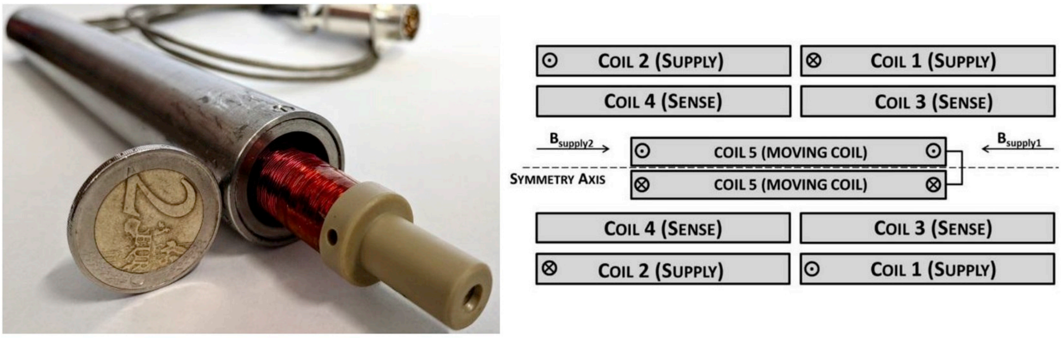
random thermal behaviour.

This paper aims at producing experimental data on the behaviour of the sensor in a controlled environment. First, it aims at understanding how the measured position varies when the temperature changes at different operating conditions. These operating conditions include different frequencies and moving coil position. The sensor's electrical components are then considered in an effort to pinpoint the parts, which contribute to the position variation.

2. Experiment setup

2.1. The ironless inductive position sensor (I2PS)

The body of the I2PS is made up of four hermetically sealed air-cored cylindrical coils, which are protected from mechanical stress with a solid shield made of steel 316LN. The I2PS is made of five coaxial coils, as shown in Fig. 1 (b); two supply coils, two sense coils, and one moving coil. The moving coil is the winding connected to the movable link whose position needs to be measured. This coil, is short circuited such that there will be an induced current in this coil. The two supply coils are fed a sinusoidal current signal and generate two equal-but-opposite magnetic fluxes. As the moving coil is displaced from the centre, the equilibrium condition is broken and the two sense voltages are different.



(a) (b)

Fig. 1. (a) The ironless inductive position sensor. (b) Longitudinal cross-section of the ironless inductive position sensor structure.

In Ref. [5], an efficient way to sense the mean temperature is conceived by superposing a dc offset to the ac supply current. In this way, the dc part of the consequent supply voltage will be directly proportional to the mean temperature along the sensor, since it will be proportional to the primary resistance. The latter is affected by the temperature according to a relation similar to $V_{dc} = R_S I_{dc} = R_S^0(1 + \gamma\Delta T)Idc = V_{dc}^0 + g_{dc}\Delta T$ where I_{dc} is the dc current superposed to the ac supply signal, R_S is the supply resistance, and R_S^0 is its value at room temperature. In addition, the dc signal on the supply coils is not reflected on any of the other windings (Faraday's law). This gives an advantage with respect to reading a localised temperature from a sensor installed under the shield.

2.2. The experimental setup and methodology

In order to study the relationship between general environmental changes in temperature and the position read by the sensor, a situation where the sensor is at constant thermal conditions has to be obtained. The sensor is placed inside a climatic chamber with air vents closed and heaters off. It is kept in this condition such that thermal equilibrium is achieved. This procedure is repeated each time the sensor is taken out of the chamber or the chamber is opened to move the moving coil. This is done such that the initial control measurement is obtained at constant temperature hence it is used as the initial position. The chamber is then set to go from room temperature to 40 °C in 2 h. It is left at 40 °C for 30 min. The readings are stopped once the climatic chamber starts to cool off. The supply and sense voltages are acquired using an NI PCI-6143 DAQ [6] and hence the position is calculated through a ratiometric reading. The temperature of the chamber is also logged. A 200 m cable is used to connect the sensor to the electronics. This procedure is repeated for different I2PS, moving coil positions and supply frequency. The same procedure is repeated with a Keysight Vector Network Analyser (VNA) in conjunction with BenchView to acquire and log the resistance and inductance of the coils as the temperature changes with different moving coil positions.

3. Results and discussion

The raw voltage amplitudes show that the ac voltage of the supply coil changes with temperature change. Since the sensor is supplied with ac current, if the resistance changes the ac voltage will also change. In reality since the relationship between the coils is based on the mutual inductance if the ac voltage changes, the change in the position should not be effected. Fig. 2 shows the change in position the sensor exhibits when the temperature is varied for different moving coil positions. In this case, the frequency of operation is kept at 1 kHz. At +5 mm, the sensor exhibits the smallest amount of position change. This can be due to uneven change in resistance of the coils.

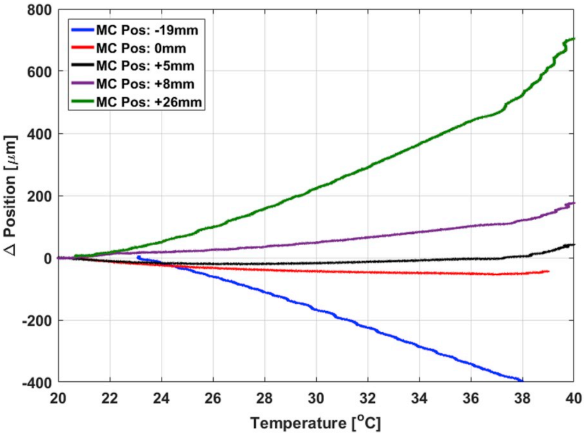


Fig. 2. Showing the change in position as the temperature is varied for different moving coil positions. A 200 m cable is used to connect the I2PS to the acquisition. The frequency of operation in this case is 1 kHz.

It is shown in Ref. [5] that, the windings' imperfections due to the multilayers, the mechanical imperfections of the shield, and the lack of homogeneity of the electrical conductivity in the shield and the imperfections of the sealant used to seal the sensor influence the sensor's voltage amplitude. It has also been stated in Ref. [5] that the sensor has a strong sensitivity with respect to the winding's imperfection, especially on the moving coil. This imperfection can result in uneven heating and hence a higher position change at other moving coil positions. The I2PS is set on an even metal plate during the heating process such that uneven heating is avoided. Nonetheless, it is evident from Fig. 2 that the temperature effect depends on the moving coil position. As the moving coil travels, further away from the centre of the sensor, the position change increases. At +5 mm, the sensor exhibits 40 μm of position change whilst at +26 mm it drifts by 700 μm for the same temperature change (approx. 20 °C). It is also noted that the change in position is always towards the electrical zero of the sensor irrespective if the moving coil is in parallel to one sense coil and not to the other. Taking the −19 mm and +26 mm examples from Figs. 2 and 3 demonstrates this by plotting the position (not position change) with respect to temperature. The left axis show the negative reading of the sensor. Note how the position changes from negative −19.55 mm to less negative −19.2 mm. On the right axis, the positive side of the sensor is presented. Note how in this case, as the temperature increases, the position also goes towards the electrical zero i.e. from +26.5 mm to +25.6 mm. These measurements are taken with the operating frequency set to 1 kHz with a cable length of 200 m.

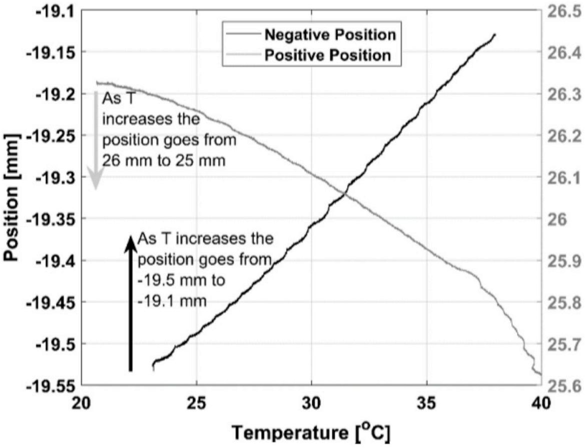


Fig. 3. Shows the temperature drifts at different moving coil positions. For both cases, the position goes towards the electrical zero.

Fig. 4 shows how the change in position due to change in temperature changes, as the moving coil position is further away from electrical zero as the frequency changes. Fig. 4 is divided into two parts: two curves have the moving coil set to −19 mm and three curves have the moving coil set to +5 mm. This is to compare the difference in moving coil position at different frequencies with respect to temperature. The two curves, which have the moving coil set at −19 mm, obey the deduction obtained from Fig. 2. The further away the moving coil is from the centre the higher the position drift. Furthermore, it shows 400 μm drift for the reading at 1 kHz and a 300 μm drift for the reading at 2 kHz.

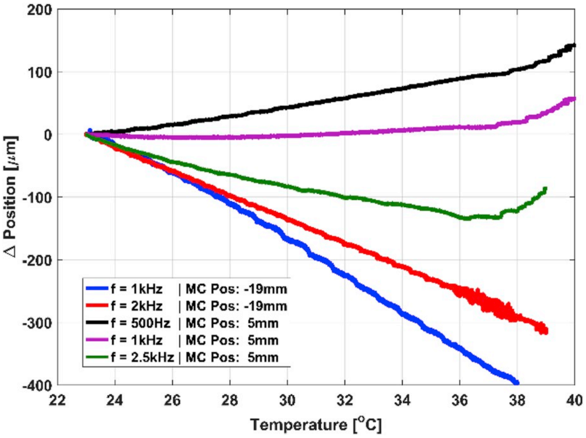
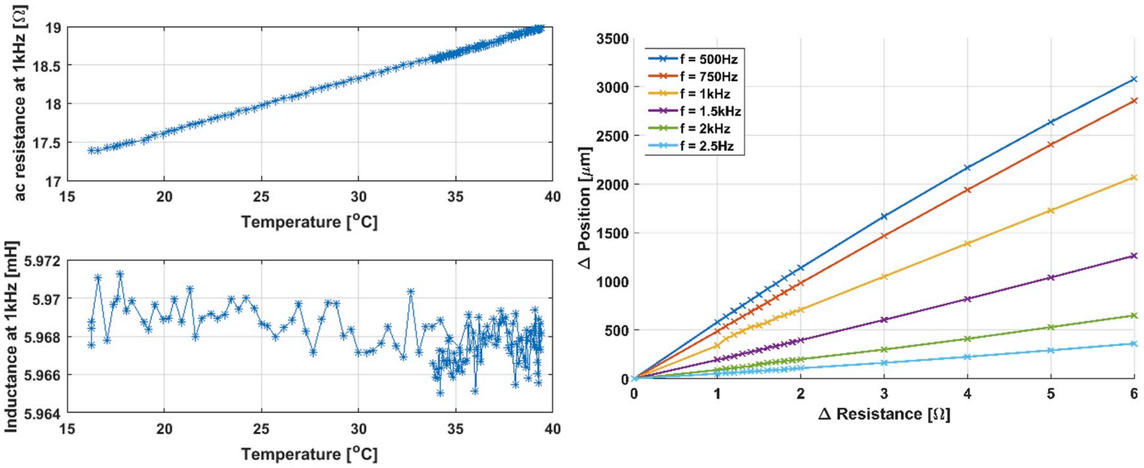


Fig. 4. Shows the change in position at different frequencies with different moving coil positions with respect to temperature change.

This means that as the frequency increases the position change decreases, as the moving coil is further away from the electrical zero. On the other hand, since the sensor is designed and optimised to operate at 1 kHz and close to the electrical zero, when the moving coil is set at +5 mm the position drift is very small (max 50 μm at 40 ˚C) at 1 kHz. As the frequency changes the position, change also increases.

To understand the key components that lead to the position change when the temperature is changed, the resistance and inductance are logged for each coil. The VNA is set to acquire a frequency range of 10 Hz to 3 kHz. In this case, the moving coil position is not varied since the coil's resistances and self-inductance is not dependent on it. The readings are similar to the one presented in Fig. 5 (a). The supply coil's resistance changes by 10 Ω and the inductance by 80 μH.



(a) (b)

Fig. 5. (a) Shows the ac resistance and inductance change of the moving coil as the temperature increases. (b) presents the position change for a manual resistance of the moving coil.

It is also noted that, up to 1.5 kHz the inductance decreases as temperature increases but for a frequency higher than 1.5 kHz the inductance increases as temperature increases. To understand the relationship between the electric components and the position the resistance and inductance is changed manually and the position is monitored. For this test, a resistance box is connected in series to the sense and supply coils. On the other hand, the resistance box substitutes the short for the moving coil. While having the sensor placed in the oven at a constant temperature the values of the resistance box is varied. For the supply coil, the resulting sensitivity is found to be 1.5 μm/Ω. There is no appreciable change due to inductance change. As for the sense coils, there is a resistance change of 200 Ω, but there is no appreciable position change when varied manually if the resistance changes equally on both coils due to the differential and ratiometric readings. On the other hand, if the temperature does not change uniformly across the sensor, then the resistance of one sense coil is different from the other. This effects the balance of the bridge leading to a sensitivity of 2.5 μm/Ω. The thermal sensitivity for one sense coil is 11 Ω/ºC.

The biggest position change is in the moving coil resistance. The inductance change for the moving coil is very small, approximately 4 μH. The resistance on the other hand changes by 1.5 Ω, which is found to be common across multiple moving coils. Fig. 5 (b) presents the relationship between the moving coil resistance and the position as obtained when a variable resistance box is added substituting the moving coil short. In order to obtain a good trend line fit and investigate the linearity of the sensor's relationship between resistance and position the resistance change is extended to 6 Ω. As noted from Fig. 5 (b), this small resistance change leads to up to 900 μm position change depending on frequency and moving coil position. In this case, the moving coil position is set to + 20 mm. The position change decreases to a maximum of 400 μm when the moving coil position is set to be 5 mm from the centre. The sensitivity to change in resistance for Fig. 5 (b) varies from 510 μm/Ω at 500 Hz to 60 μm/Ω at 2.5 kHz.

4. Conclusion

This study helps to understand why during the operation, the position drift noted is not always the same for all sensors, and it is not proportionate with the variation noted in the primary dc voltage. This is due to a combination of reasons. This case study shows that the position change at the end of the sensor is higher than that in the centre. This means that the change in position due to temperature change depends on the moving coil position. Furthermore, the change in position due to temperature change also depends on frequency of operation, which in turn depends also on the moving coil position.

In general, the resistance of the coils is the component that results in the biggest position change when the temperature is changed. Furthermore, for the moving coil, a small change in resistance leads to a big position change. Since the moving coil is not connected to any device, the temperature change is the only factor in operation that can change its resistance. Similarly, the current source and the DAQ's design do not affect the supply and sense coils' resistances respectively. Moreover, a balanced change in resistance/inductance in the supply and sense coils leads to a small change in position. This case study is important since it gives empirical documentation of the behaviour of this novel linear position sensor. It is also important since it will be used as a basis of a possible the re-design of the sensor or for the compensation algorithm.

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