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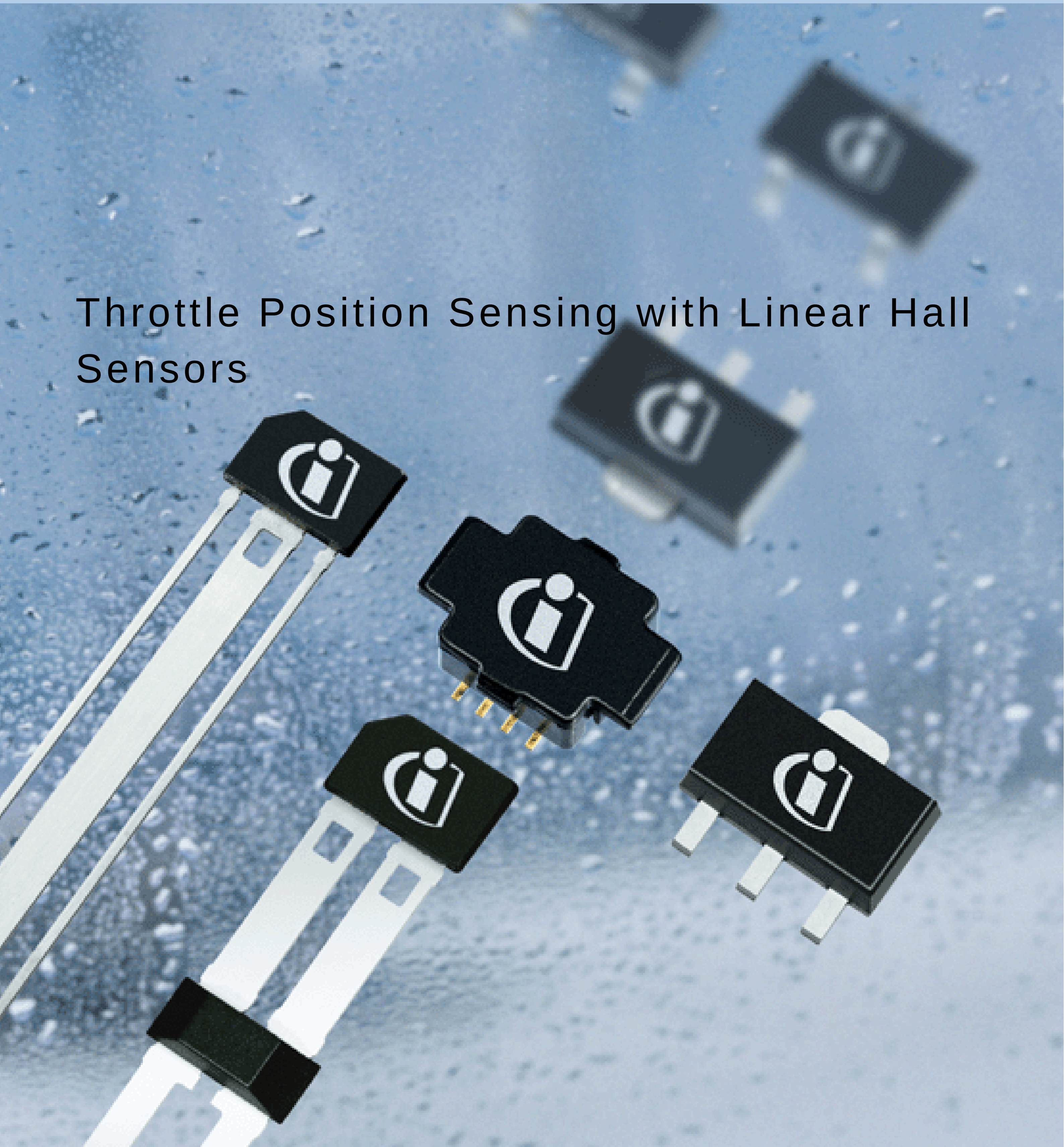
Throttle Position Sensing with Linear Hall Sensors



Sensors

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Throttle Position Sensing

1 Introduction

This application note is dedicated to magnetic sensor solutions for throttle position sensing. We first present the typical requirements and trends seen for this application. Next, we outline the common sensing principles that are currently in use and list their major benefits and drawbacks. Infineon's magnetic sensors are particularly suited for the demanding requirements of throttle position sensors and their main features are presented. The last section is dedicated to some particular aspects of magnetic throttle position sensors such as magnetic circuit design, temperature stability, reliability and interfacing and it is shown how Infineon's magnetic sensors help our customers to tackle the issues arising in tomorrow's throttle position sensors.

2 Throttle Position Sensor Requirements

The throttle is a valve mechanism allowing to modify the amount of gas flow into the cylinders of a gasoline internal combustion engine. The dominant implementation of the throttle is a butterfly valve as depicted in **Figure 1**, in which the opening angle of the valve determines the amount of air aspired by the engine. Historically, the throttle is actuated directly by the driver through the gas pedal, and accordingly there was a mechanical connection between the two (e.g. Bowden cable). Nevertheless, the throttle position had to be sensed already in those systems in order to know the proper amount of fuel to be injected. The combustion process is heavily dependent on the appropriate air/fuel mixture, leading to demanding requirements on the throttle position sensor accuracy.

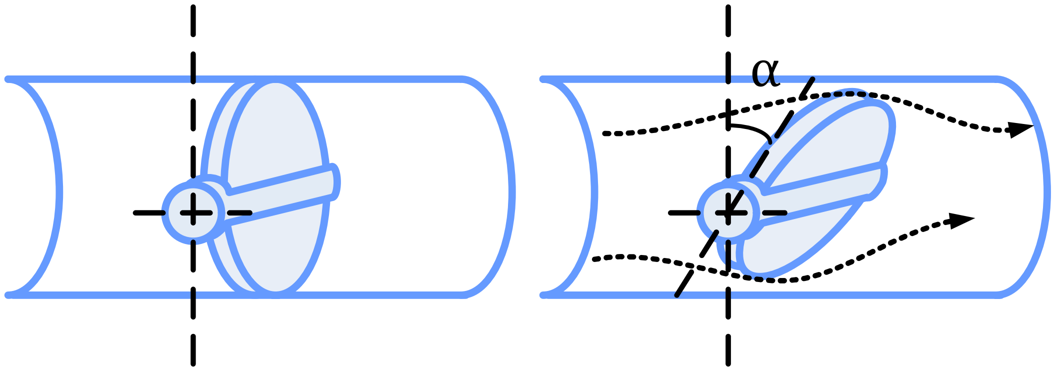

Figure 1 Schematic throttle valve in closed position and with opening angle.

Starting in the 1990s, the first electronic throttle control (ETC) systems were introduced, which did not use a physical link between gas pedal and throttle anymore but replaced it by a complete electronic control system with pedal sensor, throttle sensor and actuator as well as the necessary control unit (drive-by-wire, also known as E-gas). ETC is a technology that allows advanced features including cruise control and vehicle stability control to be implemented more easily and is extensively used in today's cars. Since the proper functioning of the ETC system is safety relevant, the safety requirements on the throttle valve sensors have been increased by the introduction of ETC.

An ongoing trend drives vehicle manufacturers towards less emissions. The combustion process is obviously extremely important in that respect and the need for a narrowly specified air/fuel ratio leads to tight requirements on throttle position sensor accuracy. The requirements are most demanding when the butterfly valve is near its closed position where minor changes in opening angle lead to big changes in air flow through the valve. Those requirements translate in tight sensor specifications, including high linearity, low hysteresis as well as small offset and sensitivity drift over lifetime and temperature to name just a few.

Additionally to these tight requirements on accuracy, modern throttle position sensors need to become more reliable. On one hand, this is due to the safety requirements already outlined above. Short-circuit and wire breakage detection, redundancy and digital interfaces with error detection algorithms are typical features that allow to address this. On the other hand, throttle body systems become more and more integrated in order to reduce system space and weight as well as material cost. A drawback of these more embedded throttle position sensors is the increased cost for exchanging a defective sensor because it becomes less easy to access. For this reason, modern throttle position sensors require technologies with even lower failure rates, favoring contactless sensor principles such as magnetic sensors.

3 Measurement Principles

3.1 Potentiometric Measurement

Potentiometers are widely used as a cheap means for measuring rotational positions. They can be readily implemented in many applications, including many in the automotive environment. Historically, position sensors for various angle detection applications were served by potentiometers, e.g. throttle valves, pedal position, EGR valve position etc. The main advantages of potentiometers include their

- Ease of implementation
- Low price
- Analog output, no signal processing needed
- Ease to add additional channels to increase reliability

However, the potentiometers also have several drawbacks

- High wear & failure rates
- Nonlinearities occurring later in lifecycle
- No digital coding possible
- Bad signal-to-noise ratio
- Redundant channels are worn out in parallel

The drawbacks of potentiometers became more and more of an issue lately for the throttle position sensor application, the main reason being the increased safety and reliability requirements. The harsh environmental conditions for throttle position sensors include high temperatures, vibrations and shocks and exposure to various liquids and gases, which can all lead to early failure of potentiometers.

Normal wear is another problem: Potentiometers typically allow about 5 to 10 mio full cycles, but as the throttle is mostly used in a small angle range (up to ca. 30°), the abrasion is biggest in this limited range. Before failing, nonlinear behavior can be observed due to wear of the resistive tracks and material build-up on the wipers, and unfortunately the worst effect is exactly in the driving range in which the sensor is used most. Finally, being a passive device, neither wire breakages and overvoltage nor internal defects can be detected and communicated to the ECU by the potentiometric sensors.

To sum up, potentiometers are a suitable solution for systems where low cost is key and reliability and safety can be traded off. Since the throttle position sensor is a safety relevant application, most new sensors are based on contactless principles nowadays.

3.2 Inductive Systems

One way of measuring a rotational position in a contactless way is by using an inductive principle. Transmit coils send a signal, which is coupled back through a rotor into receiver coils. These coils are typically integrated on a simple printed circuit board (PCB) and an IC is used to both generate the excitation signal and decode the received signal. The sensor output is flexible and can be both analog and digital, and redundancy can be achieved by integrating a second setup with a separate decoding IC on the same PCB. Although being cheap and robust, some drawbacks limit the use of this system for throttle valve sensors: The entire sensor design is rather large and can't be further shrinked. The sensors are susceptible to electromagnetic interference and the high temperature requirements of the throttle valve application tend to increase the cost for different sensor components. Consequently, the need for an increase in integration density favors the use of more compact magnetic sensor designs.

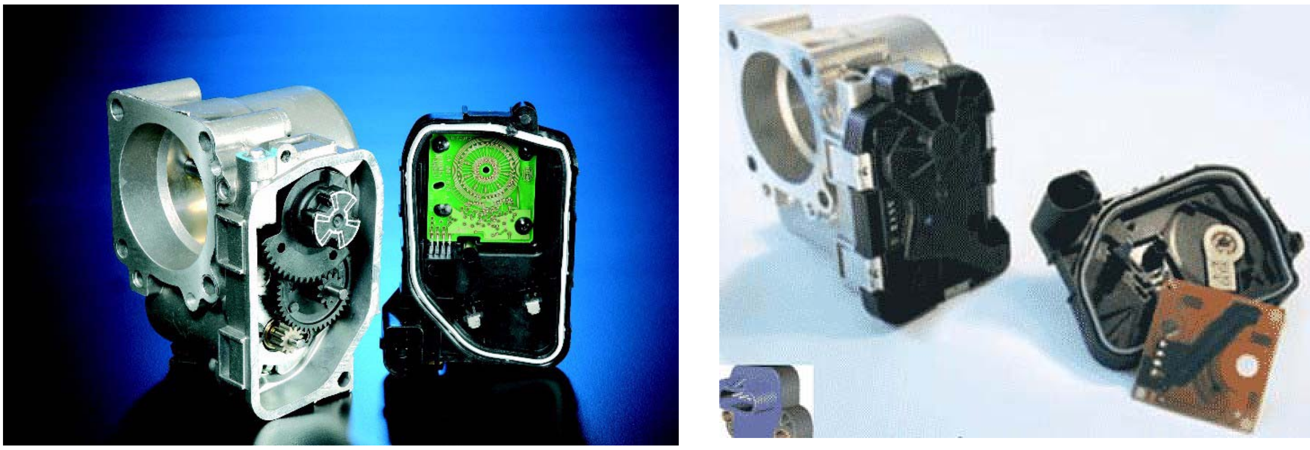

Figure 2 Sample throttle position sensors using inductive (left) and potentiometric (right) solutions.[1)]

3.3 Magnetic Systems

Following a general trend towards contactless technologies, magnetic systems also moved into the focus for throttle position sensors. Hall-effect based magnetic sensors, fully integrated on silicon, have since achieved a considerable share in this application, owing to their large list of advantages:

- Non contacting sensor principle
- No wear, highly reliable
- Direct replacement of potentiometers possible
- Digital outputs & coding possible
- Various output protocols available, including Single Edge Nibble Transmission (SENT) and Pulse Width Modulation (PWM)
- Advanced protocols allow error detection
- Excellent signal to noise ratio
- Redundancy possible
- Wire breakage, short circuit detection

The main disadvantages of the magnetic systems are the following

- Magnetic circuit needed
- Sensor needs to compensate temperature
- Stress affects sensor performance

As will be shown in the following sections, many manufacturers of throttle position sensors have managed to develop their own solution of a magnetic circuit, mostly using linear Hall sensors with a surrounding ring magnet for throttle opening angle detection. The first designs were mainly targeting a reliable replacement of potentiometers, delivering an equivalent analog output. These one-to-one replacements are now

1) Image sources: Hella KGaA Hueck & Co. press image; Bourns, Inc., internet publication

continually replaced by more advanced sensors with digital interfaces, which allow higher resolution, additional status information and even temperature information to be transmitted to the ECU. Modern magnetic sensors incorporate a wealth of features increase reliability and safety, as for example error detection and correction of on-chip EEPROM, Cyclic Redundancy Checks (CRC) in the SENT protocol or the detection of open wires and short circuits.

The drift of magnetic circuits with temperature has been successfully tackled with user programmable linear Hall sensors. The newest generation of Infineon's linear Hall sensors, for example, allows fully deterministic, state of the art second order temperature compensation of the sensitivity. Humidity and the subsequent swelling of molding material of the sensor module may lead to drift of mechanical stress on the silicon chip. Stress drift can only be treated in a limited way, but advanced stress compensation is successfully used to avert stress dependent signal drifts.

3.4 Other Technologies

Yet other technologies are used to sense a throttle position, including optical systems or incremental encoders. Although these technologies might be leading in some aspects (e.g. resolution, linearity), their drawbacks in important fields (such as cost, reliability, high-temperature capability, etc.) are so prohibitive that these sensors are currently not prevalently used in the throttle position sensor application.

	Potentiometric	**Inductive**	**Magnetic**
Reliability	Contacting principle, Prone to wear	Contactless, good	Contactless, good
Cost	Low	Medium	Higher
Size	Large	Large	Medium
Interfacing	Analog only	Digital I/F possible	Analog & Digital available
Linearity	Very good	Very good	Good
Temperature Drift	Negligible	Negligible	Can be compensated
Noise	Poor	Medium	Good
Resolution	Bad	Good	Good
Error detection	None	Can be incorporated	Various safety features implemented
Redundancy	Additional tracks, but parallel wear	Additional tracks & IC possible	Easy to assemble two redundant sensors

Table 1 Overview of performance indicators for different throttle position sensing principles

4 Infineon's Linear Hall Sensors

Infineon offers a variety of linear Hall sensors with different programming, package and interface options. This section gives a general overview of our sensor portfolio. For more detailed information, please refer to the datasheets of each product.

	Programming	Package	Interface
TLE4990	Fuses	PG-SSO-4-1	Analog
TLE4997	EEPROM	PG-SSO-3-10	Analog
TLE4998P	EEPROM	PG-SSO-3-10 PG-SSO-4-1	PWM
TLE4998S	EEPROM	PG-SSO-3-10 PG-SSO-4-1	Digital, SENT
TLE4998C	EEPROM	PG-SSO-3-10 PG-SSO-4-1	Digital, SPC

Table 2 Overview of Infineon's linear Hall sensors

4.1 TLE4990

The TLE4990 is Infineon's basic linear Hall sensor with analog signal processing and fuse programmability. The sensor is end-of-line programmable, meaning that its gain and sensitivity can be set in a two-point calibration in the module. Due to its thin PG-SSO-4-1 package, it fits in small air gaps. The TLE4990 has been field-proven in the last years and is well established for automotive applications such as gas pedal position sensing.

4.2 TLE4997

The TLE4997 has been designed to improve on some of the shortcomings of an analog compensation scheme as the one used in the TLE4990 and most competitor products, including offset and sensitivity drifts over temperature, range of the programmable parameters and accuracy. The signal processing of the TLE4997 is entirely shifted to the digital domain, making the influence of the programmed parameters completely deterministic. Temperature effects of the Hall probe can readily be compensated for using a pre-calibration in Infineon's fabrication. The TLE4997 is also the first sensor on the market that offers independent, programmable parameters for both first and second order temperature coefficients of the application sensitivity, which is especially useful for throttle position sensors as is shown in **Section 5.3**. The TLE4997 has an analog, ratiometric output and can be used as a robust replacement for potentiometers. It comes in a small 3-pin PG-SSO-3-10 package and is therefore suited for use in the limited space inside magnetic circuits such as the ones present in throttle position sensors.

4.3 TLE4998P

The TLE4998 family is the successor of the TLE4997, providing innovations on the interface side. The signal processing concept is basically based on the TLE4997 design, offering high-precision analog-to-digital signal conversion and a deterministic digital signal processing. The TLE4998P features a PWM interface, in which the duty cycle carries the Hall signal information. It offers 12-bit resolution on the output, and combined with an accurate detection on the microcontroller side, leads to a higher accuracy than what is achievable by an analog interface. More details on interfacing are given in **Section 5.6**

4.4 TLE4998S

The TLE4998S is equivalent to the TLE4998P except for the interface, which is implemented as SAE's[1)] Single Edge Nibble Transmission (SENT) standard. SENT offers a low cost alternative to CAN and LIN, but still incorporates a coded digital signal transmission with a Cyclic Redundancy Check (CRC) to check the validity of a transmission. Apart from an industry-leading 16-bit Hall value, the transmitted SENT frame includes 8-bit temperature information and a 4-bit sensor status information. These features are especially useful for the throttle application: Cutting-edge accuracy leads to higher precision of valve positioning and an optimized combustion process. The temperature information can be used for plausibility checks and to optimize the control of the throttle actuator, which is situated next to the throttle position sensor and subject to the same temperature. The status information finally allows for a massive improvement of overall system safety since information on open wires, short circuits and sensor-internal defects can be transmitted within this status nibble.

4.5 TLE4998C

The TLE4998C features a Short PWM Code (SPC) Protocol, which is an extension to the standard SENT protocol and therefore offers all the advantages already present in the TLE4998S such as high resolution, status, temperature and CRC information. The sensor does however not send out the measured values indefinitely, but only after being triggered by the ECU. This functionality allows a synchronized transmission of data. The protocol additionally incorporates the possibility to select out of up to four sensors, which are connected to a single bus line. The economical benefits of this solution are further outlined in **Section 5.6**.

1) SAE: Society of Automotive Engineers

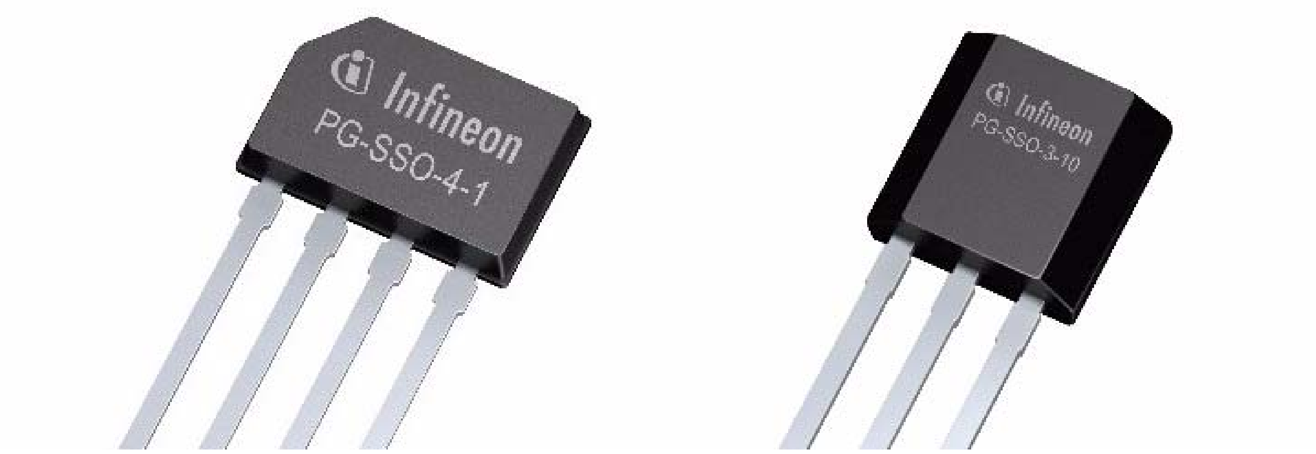

Figure 3 Linear Hall sensor packages: PG-SSO-4-1 (left, used for TLE4990, TLE4998), PG-SSO-3-10 (right, used for TLE4997, TLE4998)

5 Magnetic Throttle Position Sensors

5.1 Magnetic Circuitry

What determines the overall achievable performance of a magnetic throttle position sensor is not exclusively determined by the sensor IC performance alone, but depends to a large degree on the chosen magnetic circuitry. Here we give a review of magnetic circuits used by manufacturers explicitly for the throttle valve application. Design criteria such as achievable signal linearity, low temperature drifts, independence of mechanical tolerances and process variations, magnetic insusceptibility to external fields, number of mechanical pieces and reuse of existing parts of the applicaton (shafts, bearings, etc.) are all aspects that must be considered in the design of the magnetic circuit.

Figure 4 shows a basic design possibility to achieve a linear transfer function between angle and magnetic field. The design is based on two ring magnets with opposite radial magnetization, which are linked to the main throttle valve axis. Inside, two half-cylinders made out of ferromagnetic material are located, having a high magnetic permeability. As can be seen in the figure, the magnetic field lines are essentially perpendicular in the inner gap. Their density (a measure of the magnetic field strength in a particular location) varies linearly with the angle over a wide angular range.

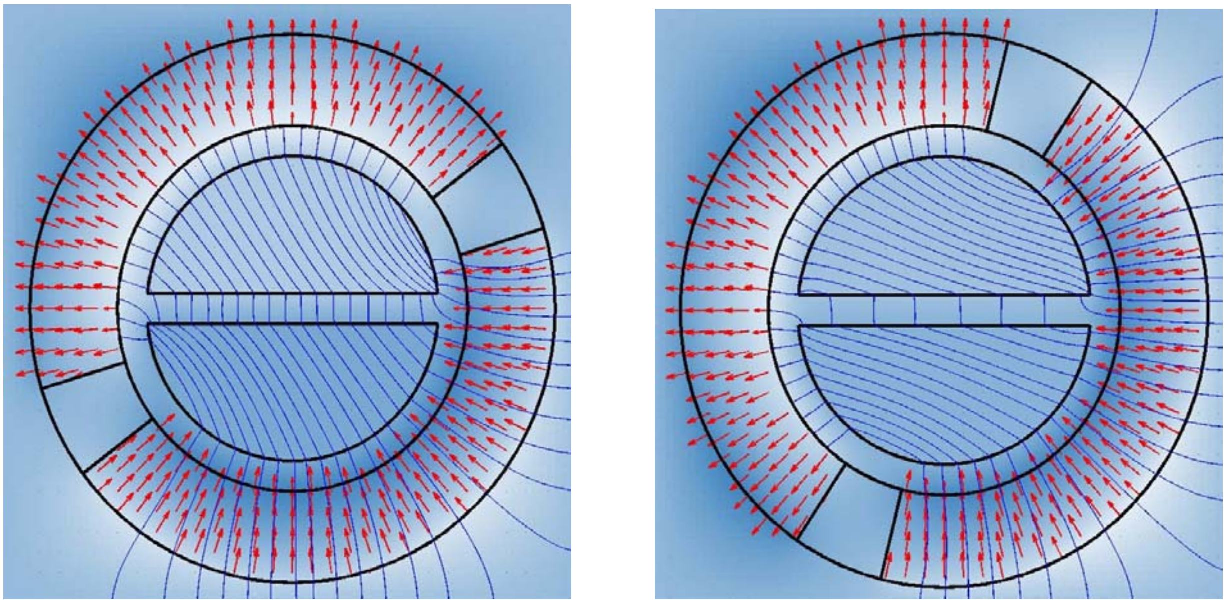

Figure 4 Sample magnetic circuit concept to map an angle onto a linear magnetic signal

Figure 5 shows a typical transfer characteristic that can be obtained in such a system. The linear range extends over a range of more than 120°, which widely satisfies the requirements of the throttle position sensor application.

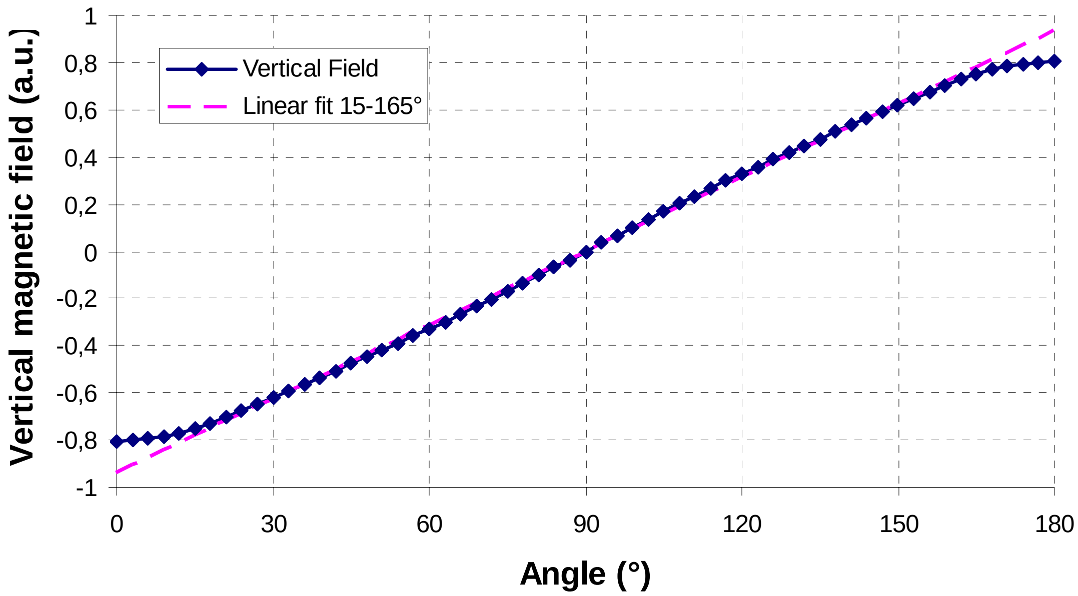

Figure 5 Mapping between angle and magnetic field for the magnetic circuit shown in Figure 4. The linear fit is calculated for 15° < angle < 165°.

Figure 6 shows the corresponding linearity measure, defined as the sensor output deviation from a linear fit as a fraction of the total measurement range.

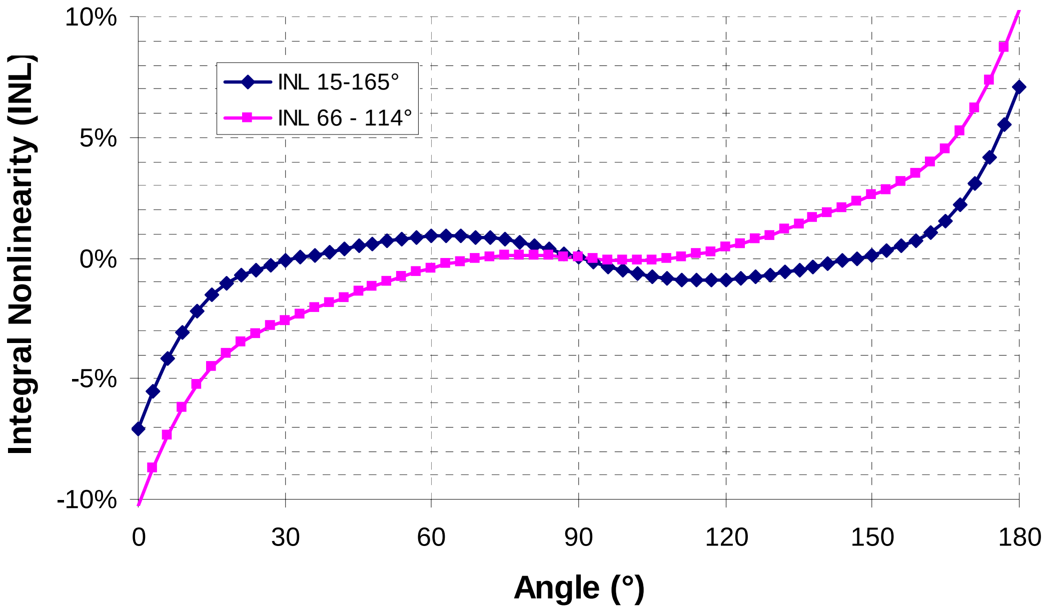

Figure 6 Nonlinearity values for the magnetic structure in Figure 4 with reference linear fits for the 15°-165° range and the 66° - 114° range.

In **Figure 7**, an example shows that through clever redesign of the basic structure, a larger field concentration can be obtained in the measurement gap. Other modifications are viable, such as reducing the size of the magnets, asymmetric magnetizations, parallel magnetizations, etc., which allows to optimize for a best possible trade-off between the application's performance needs and measures such as cost.

Please note that the designs outlined in this section are covered in patents US 5789917 and US 6356073 and should just give an idea on how to implement angle sensing with linear Hall sensors. Many similar designs are feasible and yet need to be explored.

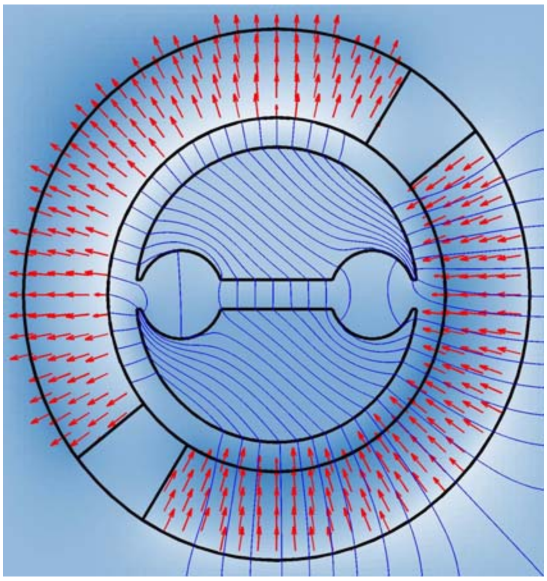

Figure 7 **Holes in the magnetic cores allow for a larger field concentration in the measurement gap.**

5.2 Linearity

Linear Hall sensors profit of a well understood Hall probe design which leads to excellent linearity, independent of temperature and lifetime. Typical measured integral non-linearity (INL) error values of magnetic sensors used to be in the order of ±0.1% of the magnetic field range (MFR). Infineon's TLE4997 and TLE4998 now have a *specified* INL error of ±0.1%, the typical achievable results being even considerably lower.

5.3 Temperature stability

The throttle valve application requires high accuracy not only at room temperature, but also at low ambient temperature or at levels up to 160°C. The drift of the output characteristic of magnetic sensors over temperature has been a problem for some time. The reason for this drift is twofold: On the one hand, the Hall probe itself does not exhibit an inherently stable behaviour in the whole temperature range. On the other hand, the application circuit has some dependency on temperature as well, which stem from a decrease in magnet strength at high temperature, impacts of changing airgaps, etc. Two important components can be identified in the drift of a magnetic sensor over temperature:

- Offset drift
- Sensitivity drift

As explained in **Section 2**, throttle valves need to exhibit best accuracy in their closed position. Since the sensitivity drift is a multiplicative error that scales with the sensed magnetic field, this error is the least important close to 0mT field. It is therefore a good choice to map the 0mT position as close as possible to the closed valve position. The magnetic circuit in **Figure 2** has a linear range of approximately ±80° around the 0mT position, a possible choice is therefore to map the closed position to -10° and the open position to +80° of the magnetic circuit for a 90° working range.

Infineon offers sensors with compensation algorithms for both offset and sensitivity drifts. The TLE4997 and TLE4998 implement an offset compensation so that the sensors have an outstanding stability of the zero field output. The magnetic offset drift over temperature is an important performance measure for maximum accuracy in the closed position. Infineon's linear Hall sensors exhibit industry-leading offset drift performance: **Figure 8** shows typical measurements of the offset drift behaviour of the TLE4997, compared with two comparable competitor products. The corresponding angle error can be deduced via the sensitivity of the magnetic circuit, which is roughly on the order of 1mT/° for systems as the one depicted in **Figure 2**. A drift of 100µT then corresponds to only 0.1° angle error, which is even exceeded by the typical performance of the TLE4997.

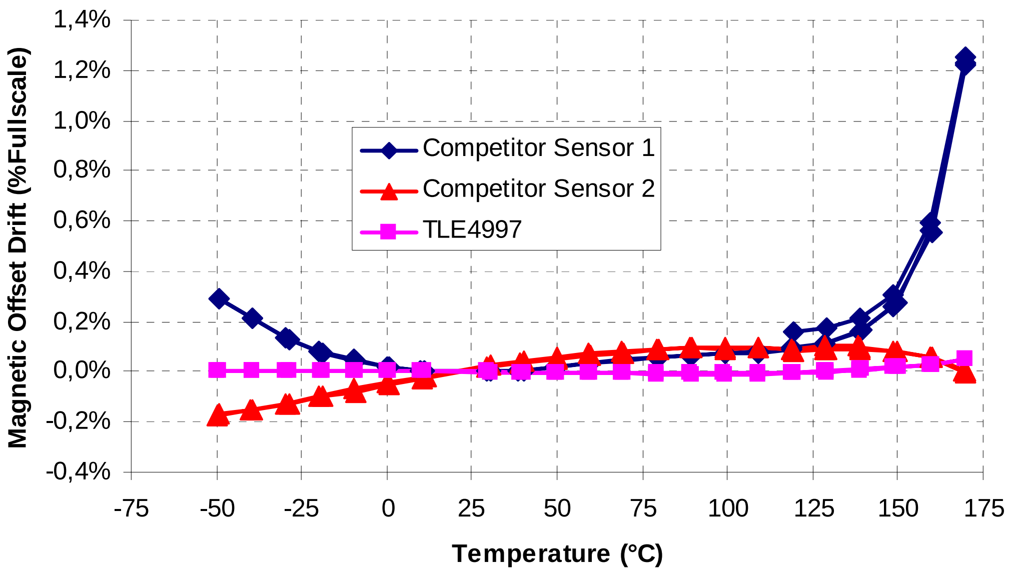

Figure 8 Comparison of magnetic offset drift performance of the TLE4997 with competitor analog linear Hall sensors (all programmed to a sensitivity of 100mV/mT with full scale -25mT to 25mT)

Since the sensitivity is affected by both the Hall probe and the application, its compensation parameters are available to the customer. Independent parameters for linear and quadratic compensation can be programmed by the customer and excellent stability over temperature can therefore be achieved. **Figure 9** shows a typical measurement of magnetic field drift over temperature for a throttle valve with a magnetic circuit similar to the ones described above, condensing the effects of the magnets and ferromagnetic material over temperature. The relative change in magnetic field is shown for measurements in both an open and closed position. The behaviour is slightly different for the two positions, which can be explained by small changes in the permanent magnet's operating point. Depending on accuracy requirements, the compensation coefficients are either derived from the closed position measurements or from an average between open and closed position.

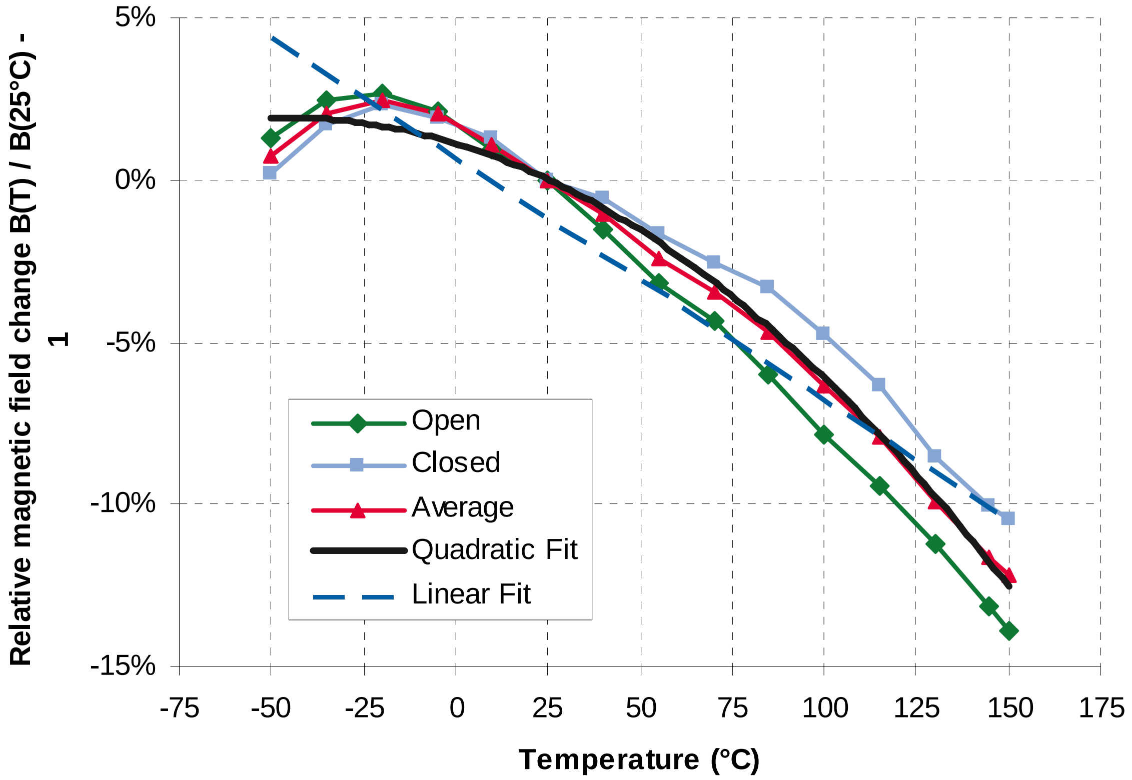

Figure 9 **Sample measured magnetic field drift of the magnetic circuit in a throttle position sensor**

It can clearly be seen that the sensitivity does not vary linearly with temperature, but its characteristic is closer to quadratic. Infineon's TLE4997 and TLE4998 are the first sensors on the market that offer an independent user programming of both linear and quadratic sensitivity drift. In **Figure 9** it can clearly be seen that the 2nd order sensitivity compensation (quadratic fit) is superior to a first order compensation (linear fit) for throttle position sensors.

5.4 Noise

The achievable resolution of systems based on linear Hall sensors has long been limited by noise on the sensor output, in such a way that no advantage over potentiometers could be achieved in this respect. Infineon's TLE4997 high accuracy linear Hall sensor has improved this measure considerably and specifies a peak-to-peak noise smaller than 0.1% of the field range. The possibility of coding information in a digital interface has further lowered the achievable noise. Infineon's TLE4998 with SENT interface has a specified peak-to-peak noise of 2.5LSB$_{12}$, which corresponds to 0.06% of the full range. Typical measured root-mean-square (RMS) noise levels are as low as 0.01% of field range for the TLE4998.

5.5 Reliability

Due to cost and environmental reasons, a general trend in powertrain design goes towards more integrated and embedded systems, reducing building space and weight. Unfortunately, systems that have been easily accessible before are now highly integrated and can't be changed comfortably anymore, leading to high cost if failed parts need to be replaced. Since sensors tend to be entirely embedded into systems including motors and other mechanical parts, a whole module needs to be replaced if a single sensor fails. This is no different for the throttle valve application, where throttle motor, position feedback sensor and the valve itself become more and more densely packed. It goes without saying that reliability is a key requirement needed to support this trend, which led to the shift towards contactless systems already discussed above. Position sensors based on the Hall effect are well suited to those systems, allowing significantly more repetitions than comparable systems based on contacting principles.

Additionally to the inherent reliability of the magnetic sensors, manufacturers often make use of redundancy for the throttle valve sensor since the drive-by-wire feature is safety relevant. Infineon's analog linear Hall sensor TLE4997 can be readily used to replace the typical potentiometer setup having two units with inverted output characteristics. For future systems, the TLE4998S is the right candidate: Additionally to the other features, the sensor transmits status information, an unparalleled 16-bit digital signal value, temperature information and a cyclic redundancy check nibble in its SENT protocol, achieving even higher levels of safety through signal integrity checks.

5.6 Interfacing

Classic throttle position sensors, including the ones using potentiometers, have an analog output and are connected to the A/D converter input of a microcontroller. The TLE4997 is an excellent possibility for a one-to-one replacement of potentiometers, leading to low cost and risk for design changes on the microcontroller side.

The TLE4998P can be employed to economize the A/D interface on the microcontroller, only requiring a common capture & compare (CAPCOM) unit to sample the sensor's PWM signal. The PWM protocol interpretation is extremely simple and does not require an extensive signal processing.

The TLE4998S features the SENT protocol (SAE J2716), a low-cost alternative to CAN and LIN interfaces, allowing higher data resolution than PWM or analog interfaces. The system implementation of a SENT interface can be done for example using Infineon's TC1797 microcontroller. It uses 4 Local Timer Cells in the General Purpose Timer Unit, coupled with one direct memory access (DMA) controller per SENT channel. A typical load of less than 1% per channel is estimated for the whole SENT decoding routine in this TriCore at 180MHz. If a PCP is used for the decoding, the PCP load would amount for less than 5% at that same frequency.

The last interfacing option is offered by the TLE4998C, featuring a Short PWM Code (SPC) format. This format allows some degree of command communication from the microcontroller to the sensor. Three modes are available:

- Sync mode: The sensor sends a standard SENT frame after being triggered by the microcontroller
- ID mode: Up to four sensors can be connected to the same microcontroller input line and are individually triggered using varying master pulse lengths. Cables and connectors, microcontroller input ports, CAPCOM units, interrupts and DMA channels can be saved in this variant among others
- Dynamic range selection: The sensor's input sensitivity can be dynamically chosen

6 Conclusion

Infineon's portfolio of high precision, programmable linear Hall sensors is a perfect match to today's challenging requirements of high reliability, high accuracy throttle position sensors. Both analog and digital interfacing options are available to match the different control unit designs, programmable parameters on the chip's EEPROM offer a high degree of customization and state of the art digital compensation ensures a proper functioning even under extreme environmental conditions as seen in the throttle application. That's why we believe Infineon's linear Hall sensors are the right choice for our customers' magnetic throttle position sensor designs.

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