Integrated Angle Sensor Based on the Magnetoresistive Effect

1. Introduction

Magnetoresistive sensors are sensitive to magnetic field variations and fulfil today's demands of contact- and wear-free solutions for direct angle measurements. Integrated sensor conditioning electronics allow for solutions with low unit costs and minimised built-in space. The „sensor + electronics"-system described in this document overcomes many disadvantages of common competitive measurement techniques, providing an accurate, reliable and flexible solution to many angle measurement tasks in various application fields (e.g. agricultural, automotive, consumer, medical).

2. Magnetoresistive Sensor

The property of a current-carrying magnetic material (e.g. permalloy: 20% Fe, 80% Ni) to change its resistivity in the presence of an external magnetic field H is called magnetoresistive (MR) effect [i]. When no external magnetic field H is present, the permalloy has an internal magnetization vector parallel to the current flow. If an external field H is applied, the internal magnetization vector will rotate around an angle α. As a result, the resistance R of the permalloy will change ($\rightarrow \Delta R0$ = approximately 1 - 2% of R0) as a function of the rotating angle α (formula, Fig. 1).

$$R = R_0 + \Delta R_0 \cos^2 \alpha$$

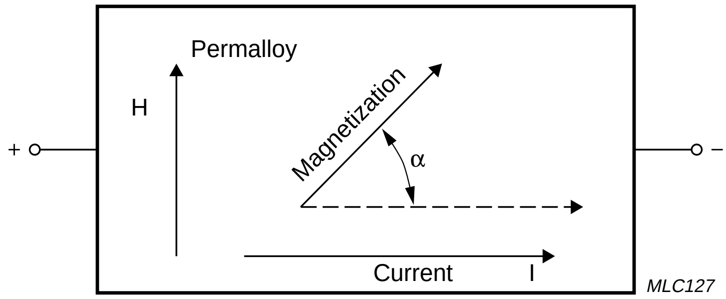

Fig. 1: The magnetization effect in permalloy

To achieve an accurate angle measurement [ii], the only condition is that the internal magnetization vector directly follows the external magnetic field vector. This is done by applying an external field with approximately > 100 kA/m, so that the two vectors are virtually parallel to each other. A set-up to determine the angle position of a shaft and the advantages of this direct angle measurement by detecting the field-direction are shown in Fig. 2.

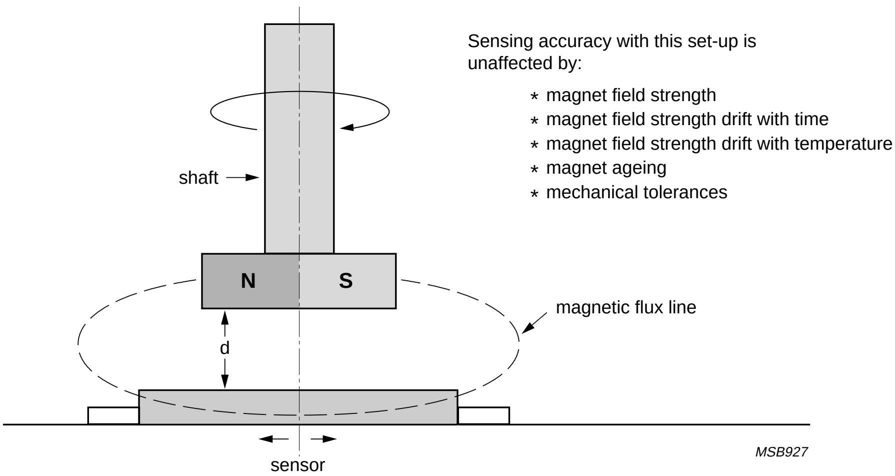

Fig. 2: Arrangement of sensor and magnet

The Philips MR sensors are etched on a silicon substrate, with four permalloy strips arranged in a Wheatstone bridge configuration. According to the basic relationship ($R = R0 + \Delta R0 \cos^2(\alpha)$) the bridge output signal is proportional to sin(2α).

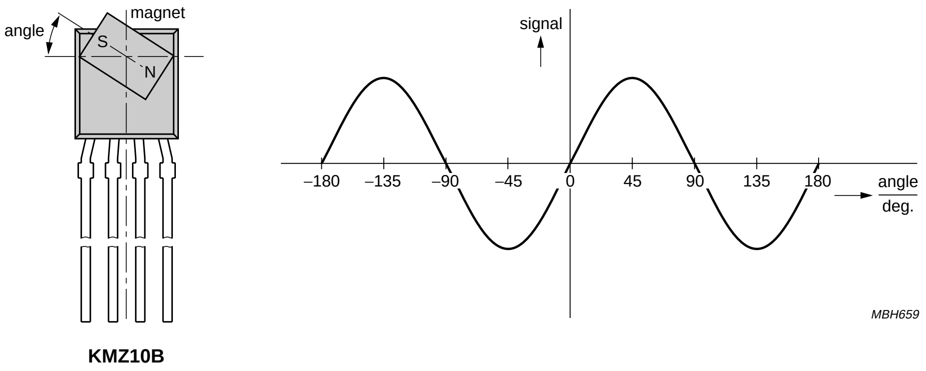

Fig. 3: Angle measurement with the MR Sensor KMZ10B

As shown in Fig. 3 the sensor translates a single rotation of the target (360°) into a 720° output signal (2 complete sine waves). Consequently a single-sensor-system is limited to unique angle measurements in a range of ±45° or 0° to 90° respectively. Since many applications require wider angle ranges, a second MR sensor is used to extend the range. If two sensors are accurately positioned at 45° to one another mechanically, then the output signals have an electronically phase shift of 90°. Therefore the sensor signals represent sin(2α) and cos(2α), and as the quotient of both signals equals tan(2α), α can be calculated using the arcustangens function. Based on this double-sensor-system angle ranges up to 180° can be detected.

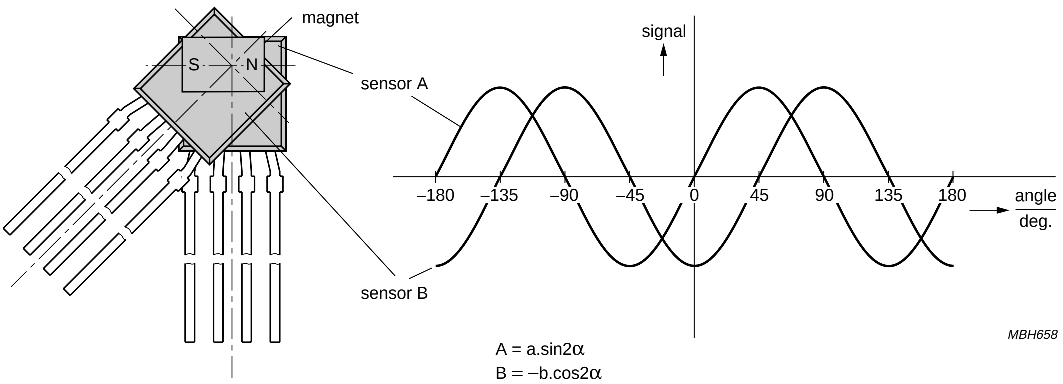

Fig. 4: Angle measurement with two MR sensors

Fig. 5 shows the practical realization of a double-sensor-system. The MR double-sensor KMZ41 [iii] provides 8 MR resistor networks, connected as two individual Wheatstone bridges, aligned with 45° shift in their sensitive magnetic direction.

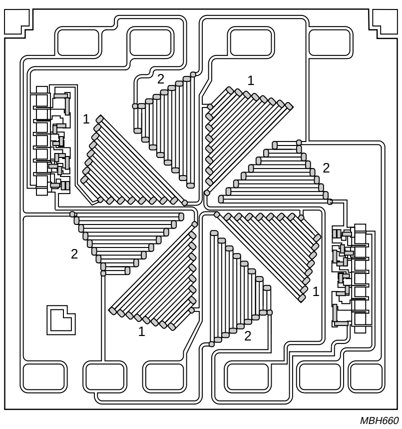

Fig. 5: Layout of the MR double sensor KMZ41

3. Sensor Conditioning Electronics

3.1 Signal processing

Philips has developed an ‘one-chip’ application specific integrated circuit (ASIC) solution (see Fig. 6, [iv]) which combines a sine and cosine wave into a single linear output voltage. The input signals might come from the MR double sensor KMZ41 and in this case the signal conditioning electronics UZZ9000 provides good results for linear angle measurements. This integrated circuit can also be used for all other applications (e.g. resolver) in which a sine and cosine signal have to be transferred in one output characteristic.

The main signal path of the IC consists of two analog to digital converters (ADCs), the digital signal processing (an algorithm as well as a customized adjustment of the output characteristic) and a digital to analog converter (DAC). The usage of an expensive quartz- or ceramic-oscillator is needless, because the processing is independent of an absolute time basis. For this reason a simple on-chip RC-oscillator was implemented. A serial interface is used to enter the trim mode, which is once necessary to compensate for the MR sensor offsets, and production tests. This interface is exclusive used by Philips as the supplier. The „sensor + electronics“-system (KMZ41 + UZZ9000) is a ready-to-use module which enables the user to set both the angle range to be measured and the zero point in wide ranges.

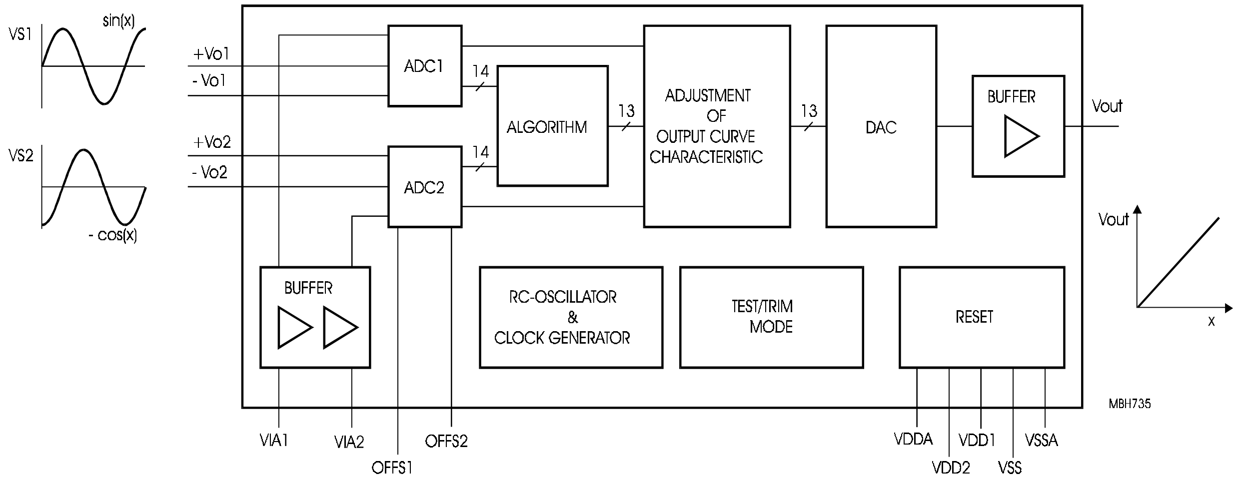

Fig. 6: Block diagram of the „one-chip“ ASIC solution, UZZ9000

Each sensor signal (VS1, VS2) feeds a 14-bit ADC consisting of a sigma-delta-modulator followed by a digital filter. The two digitized sine waves are then processed with the CORDIC algorithm (**CO**ordinate **R**otating **DI**gital **C**omputing). CORDIC is an efficient way to perform the arcustangens function, because only shifting and adding operations are necessary [v].

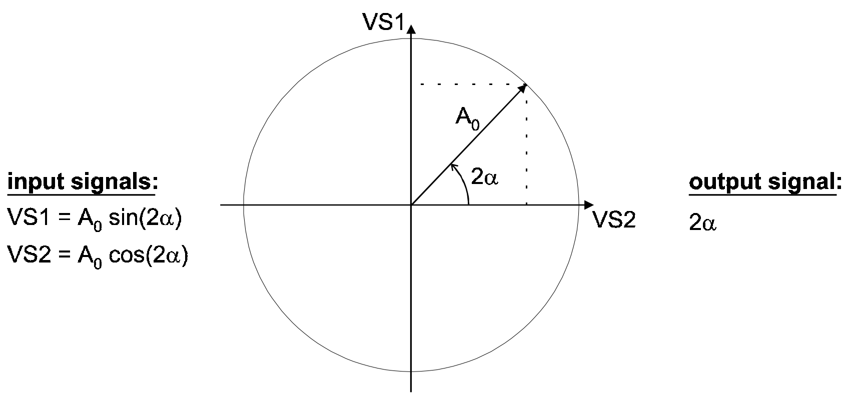

Fig. 7: CORDIC algorithm

A further advantage of this signal processing can be found in the cancellation of the temperature drift of the sensor amplitude A_0. Temperature changes cause variations of A_0 (size of circle shown in Fig. 7), but the angle is unaffected by this. In combination with the MR double sensor KMZ41 CORDIC offers a basic output angle range of 180° regardless the input angle range. Users who will not benefit from this basic range have the possibility to adjust smaller angle ranges. Furthermore the zero point of the output curve can be shifted to compensate for location deviations. These two characteristics (angle range, zero point) are fixed by two off-chip voltages (VIA1, VIA2) which are once converted to the digital domain after power-on of the ASIC.

3.2 Output characteristic

Since today's applications work typically with analog output signals (e.g. potentiometers), the resulting code for the angle is transferred back to the analog domain. It has to be highlighted that this output voltage VOUT (see Fig. 8) is a ratiometric one (normalized to IC supply voltage VDD), handed out by a 13-bit DAC. The x-axis shows the mechanical angle α within a range of $\alpha2-\alpha1$. Above and below the valid measuring voltage from 5 to 95 %VDD a „forbidden zone" of 1 %VDD borders. If the adjusted angle range is exceeded (< $\alpha1$ or > $\alpha2$) then the output curve runs horizontal within the voltage range from 5 to 6 %VDD or 95 to 96 %VDD respectively (Remark: If the adjusted angle range is 180° then the output curve will never run horizontal.). If the basic angle range of 180° is exceeded then the output voltage changes from upper to lower „horizontal voltage" (or vice versa), so that the output curve is repeated periodically.

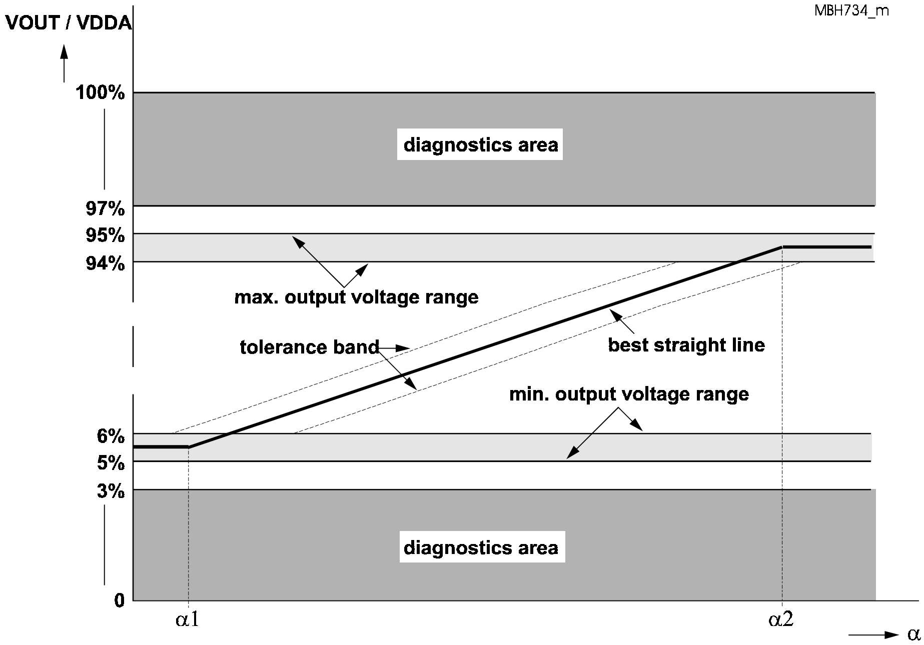

Fig. 8: Output characteristic

A further feature of this device is that it will run into one of the diagnostic areas as soon as one of the following conditions is fulfilled:

- short circuit between output voltage VOUT and GND (R < 1 Ω)
- short circuit between output voltage VOUT and supply voltage VDD (R < 1 Ω)
- disconnection of supply voltage VDD (for pull down resistor configuration only)
- disconnection of GND (for pull up resistor configuration only)
- loss of the magnet

Data of the signal conditioning electronics UZZ9000 combined with the MR double sensor KMZ41 are shown in Tab. 1:

Symbol	Parameter	min.	nom.	max.	Unit
VDD	supply voltage (no protection against overvoltage or reverse polarity)	4.5	5	5.5	V
ICC	supply current			14	mA

VOUT	ratiometric output voltage: valid measuring range lower voltage for angles < α1 upper voltage for angles > α2 diagnostic areas: upper area lower area	 5 5 94 97 0		 95 6 95 100 3	 %VDD %VDD %VDD %VDD %VDD
$\alpha2-\alpha1$	angle range (adjustable in 10° steps)	30		180	degree
$\Delta\alpha$	zero point of output curve (adjustable in 0.5° steps)	-5		5	degree
R, H	resolution, hysteresis		0.05	0.1	degree
A	accuracy (see tolerance band in Fig. 8) depends on $\alpha2-\alpha1=30°$ angle range $\alpha2-\alpha1=30°$ $\alpha2-\alpha1=100°$ $\alpha2-\alpha1=100°$ $\alpha2-\alpha1=180°$ $\alpha2-\alpha1=180°$	 -2.5 -0.8 -0.9 -1 -0.7 -1.4		 2.5 0.8 0.9 1 0.7 1.4	 %VDD degree %VDD degree %VDD degree
T_{amb}	ambient temperature	-40		+140	°C
t_R	response time			1.2	msec

Tab. 1: Data of the „sensor + electronics“-system, KMZ41 + UZZ9000

3.3 Application circuit

To reach a maximum of compatibility with control units the output of the ASIC can be connected to a pull down or pull up resistor. A simple circuit with a pull down configuration is shown in Fig. 9. Each of the two ICs, sensor and electronics, are mounted in small outline packages. The external voltages VIA1 (zero point), VIA2 (angle range), OFFS1 (sensor offset 1) and OFFS2 (sensor offset 2) must be derived from the IC supply voltage by using resistive voltage dividers (→ R1 to R4).

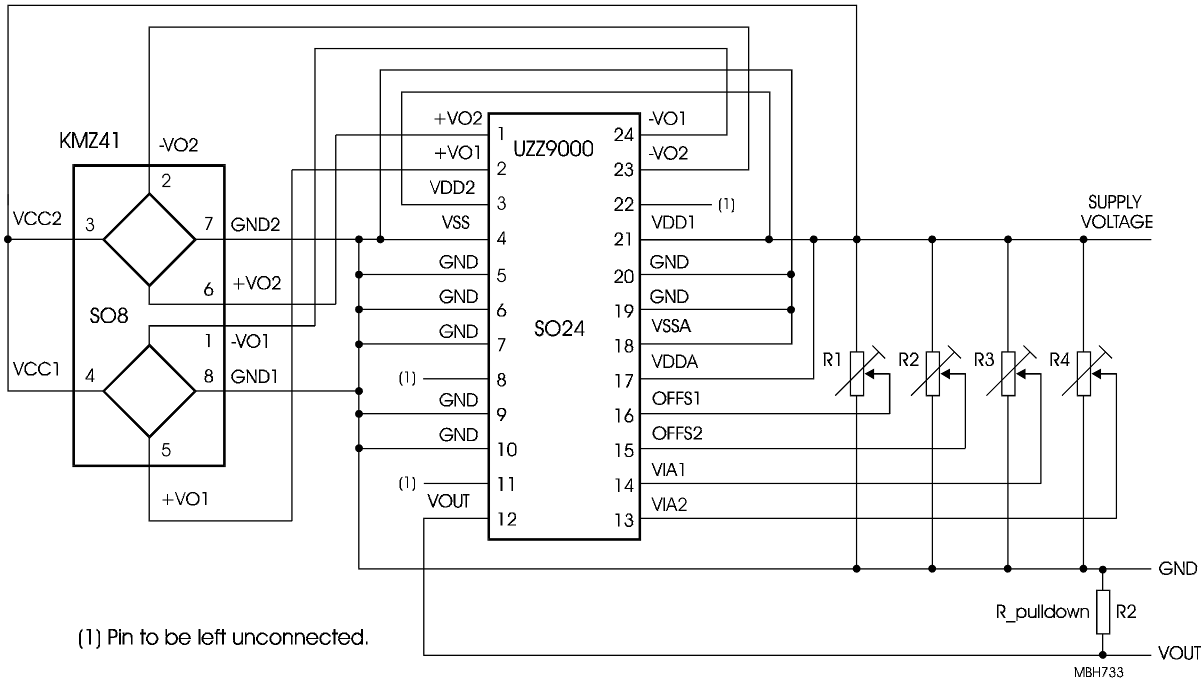

Fig. 9: Application circuit

To adjust the angle range and zero point prescribed voltages need to be connected to VIA1 and VIA2. To minimize nonlinearity errors of the output characteristic it is necessary to make a magnetic adjustment to cancel the offsets of the two sensor bridges. Therefore the serial interface of the UZZ9000 needs to be operated and a correction has to take place by trimming the voltages OFFS1 and OFFS2.

4. Conclusion

The signal conditioning electronics UZZ9000 combined with the MR double sensor KMZ41 is an angle sensing solution which delivers an absolute and linear measurement over a wide range. The system allows the user to adjust the angle range and zero point by his own, adapted to his specialized applications. This wear- and contact-free measurement still works under extreme temperatures and is for example unaffected by

- dust and dirt
- changes in magnetic tolerances
- variations of the mechanical set-up.

Digital sensor interfaces or even networking of sensors will be an integral part of future systems. Thus it is important to prepare the basis for the required digital output signals. The actual realized analog output of the sensor electronics UZZ9000 represents only one possibility to hand out the calculated angle. Due to the digital signal processing different digital interfaces (e.g. PWM, I^2C, CAN) might be offered to react as quick as possible to the requirements of the market.

Literature

[i] „GENERAL Magnetic field sensors“, Discrete Semiconductors, Data Sheet, File under Discrete Semiconductors, SC17
[ii] „GENERAL Angular measurement“, Discrete Semiconductors, Data Sheet, File under Discrete Semiconductors, SC17
[iii] „KMZ41 Magnetic field sensor“, Preliminary specification, Discrete Semiconductors, Data Sheet, File under Discrete Semiconductors, SC17
[iv] „UZZ9000 Sensor Conditioning Electronics“, Objective specification, Discrete Semiconductors, Data Sheet, File under Discrete Semiconductors, SC17
[v] “ A 540-Mhz 10-b polar-to-cartesian converter”, G.C. Gielis, IEEE Journal of Solid-State Circuits, Vol. 26, No 11, Nov. 1991, p. 1645 - 1650

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