**DISCRETE SEMICONDUCTORS**

# DATA SHEET

# General
## Sensor systems

1997 Jan 09

File under Discrete Semiconductors, SC17

**Philips**
**Semiconductors**

PHILIPS

## ANGLE MEASUREMENT

### Contents

- Principles and standard set-ups
- Philips sensors for angle measurement
- Real-life measurement applications
- Information for advanced users and applications
  - Additional measurement set-ups
  - Magnets
  - Angle sensor eccentricity.

### Principles and standard set-ups

The principle behind magnetoresistive angular measurement is essentially simple: as explained in the general section, the MR effect is naturally an angular effect. The resistance of the permalloy strip depends on the angle $\alpha$ between the internal magnetization vector of the permalloy strip and the direction of the current through it.

When using the MR effect in sensors for measuring angles, no linearization using a barber-pole sensor layout Is required and the original direct relationship between the resistance R and angle $\alpha$ ($R = R_o + \Delta R_o \cos^2\alpha$) is valid.

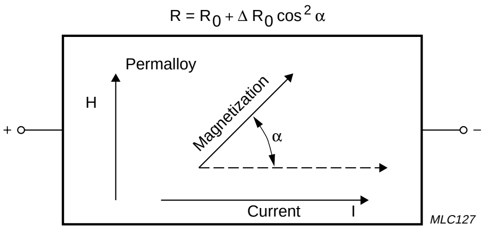

Fig.1 The magnetization effect in permalloy.

To achieve accurate measurement, the only condition is that the internal magnetization vector of the permalloy directly follows the external field. This is done by applying an external field very much greater than the internal field so the sensor is ‘saturated’; with today’s sensors, this is normally achieved by having a magnetic field strength of approximately 100 kA/m in the sensor plane. In this set-up, (Fig.3) angle is measured directly by detecting the field-direction and the set-up is independent of:

- Magnet field strength
- Magnetic drift with time
- Magnetic drift with temperature
- Ageing, and
- Mechanical tolerances.

which allows for reduced system tolerances and pre-trimming of the sensor. This is the solution adopted by Philips in its KM110B modules. The only precaution that need be taken with this technique is ensuring the field directions during trimming match the field directions after assembly.

There is ongoing development of sensors that can be placed in this ‘saturated’ condition using steadily smaller field strengths and this significantly reduces system costs, because relatively inexpensive normal ferrite magnets can be used rather than other, more costly permanent magnets.

**Note:** all Philips sensors and modules have in general been designed to be used with this ‘direct’ method. However, there are other techniques that can be used: for information on other methods, refer to ‘Information for advanced users and applications’ later in this chapter

The aim in angle measurement is to influence, as fully as possible, the internal magnetization of the sensor by the application of an external magnetic field, so the magnetization follows as closely as possible the external magnetic vector. If, as recommended, a typical ‘saturation’ field of 100 kA/m is applied, due to the vector addition of this external field with the internal magnetization of 2 kA/m, the result is a systematic error of about 2%. This error is eliminated during the production of Philips modules by trimming.

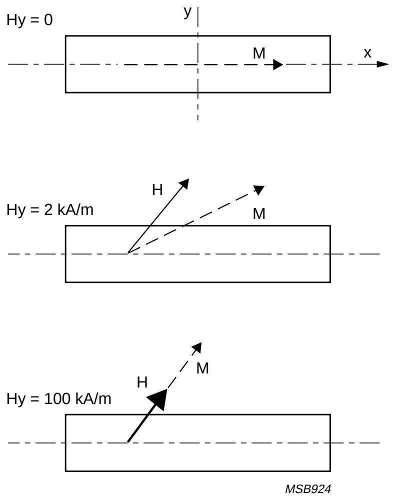

Fig.2 Internal field vectors align with a stronger external field.

When using a sensor/magnet combination in angular measurement applications, the magnet is placed on the target, in front of the sensor (which is positioned so that its internal magnetization vector is parallel to that of the magnet at the reference point).

When the target turns, the magnet is rotated in front of the sensor and the angle of the external field changes relative to the internal field of the permalloy strips. This causes the internal magnetization vector of the sensor to rotate by an angle $\alpha$, aligning itself with the external field (see Fig.2).

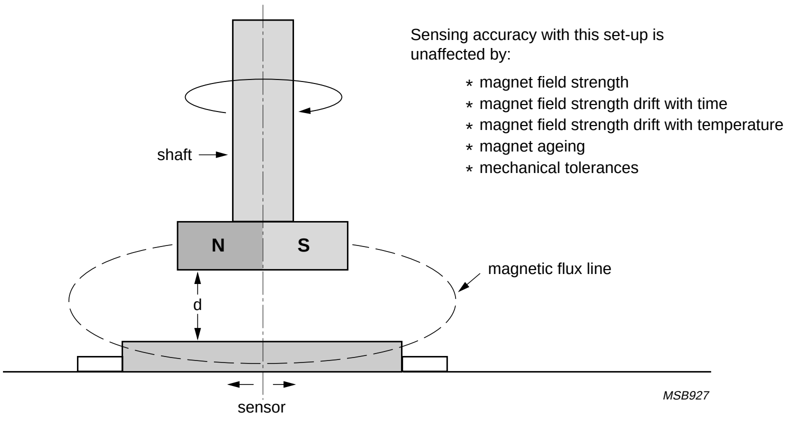

Fig.3 Arrangement of sensor and magnet.

### EXTENDING ANGLE RANGE

From the basic relationship (see Appendix 1 on the magnetoresistive effect):

$(R = R_o + \Delta R_o \cos^2\alpha)$

it can easily be shown that:

$R \approx \sin 2\alpha$

If a sensor is used in non-linearized mode, then it translates a single rotation of the target (360°) into a 720° output signal (2 complete sine waves). This means that the output signal of the magnetoresistive sensor offers good linearity only within the angle range of ±15° (where $\sin\alpha \approx \alpha$). If a sine wave output is acceptable in the application (for example if there is a microprocessor in the system which can convert the output sine curve to a linear relationship), the angle range can to be extended to ±35° (see Fig.4). Resolution is reduced at the ends of the range, but behaviour is unaffected in the middle of the range.

To obtain a solution for angles in the range ±90°, two MR sensors are used (see Fig.5). If they are accurately positioned at 45° to one another mechanically, then electronically their output signals are 90° out of phase. Therefore the output signals from the two sensors represent $\sin 2\alpha$ and $\cos 2\alpha$ respectively, and as $\sin 2\alpha / \cos 2\alpha = \tan 2\alpha$, $2\alpha$ and therefore a can be easily calculated.

**Note:** if the sensors are arranged in parallel, (positioned at 0° degree to one another) this set-up is excellent as a redundant set-up (although of course the angle measurement range will be limited). With this set-up, both sensors are influenced equally by the external magnet, so redundancy is achieved with only one external magnet and the need for signal conditioning is reduced.

Although in principle the set-up in Fig.5 is simple, two factors have to be addressed before this solution for the measurement of angles up to 90° is economically viable.

Firstly, there has to be an economic way of combining the $\sin 2\alpha$ and $\cos 2\alpha$ signals into a single signal representing the angle $\alpha$. To answer this need, Philips is developing an ASIC (Fig.6) with the required signal conditioning on one chip and offering digital interfacing (solutions for PWM, serial bit stream and CAN.bus are now possible).

Secondly, the sensors have to be aligned mechanically at exactly 45°. This is achieved using advances in magnetoresistive manufacturing technology, where two overlapping sensor bridges are etched on the same substrate, using a photo-mask process. This process has extremely high accuracy, more than sufficient for this application

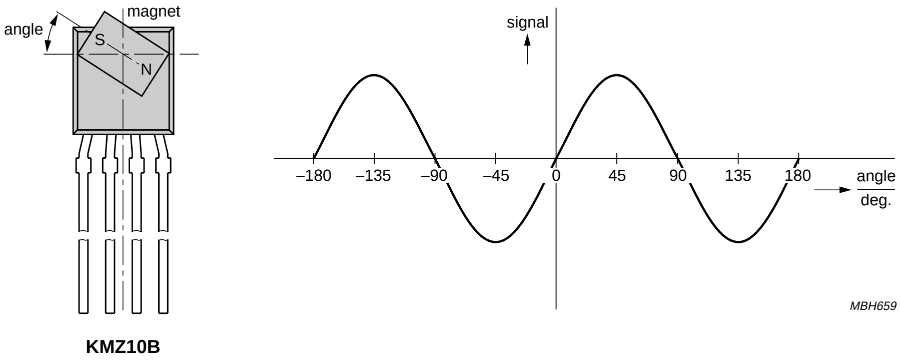

Fig.4 Angle measurement with a KMZ10B.

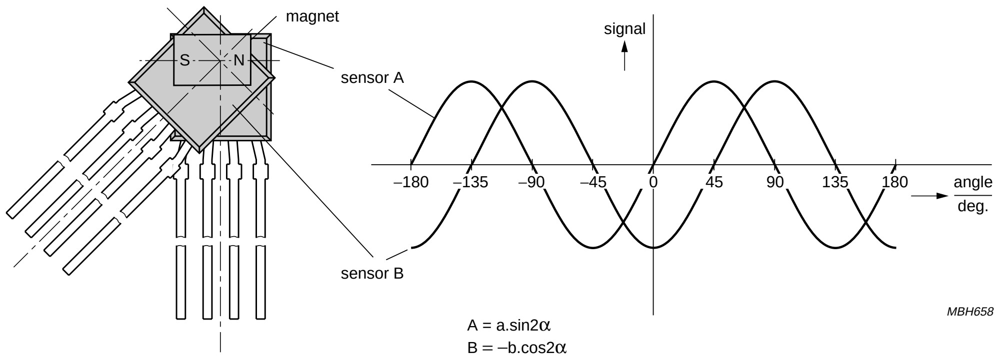

Fig.5 Angle measurement with two sensors.

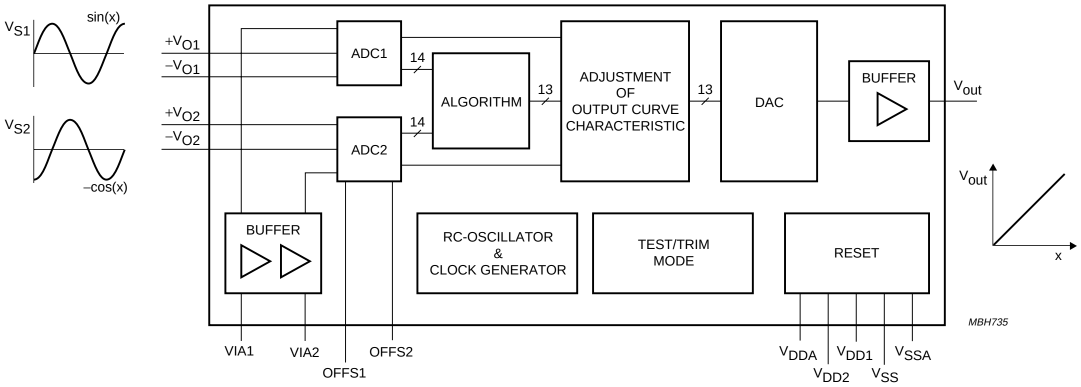

Fig.6 Block diagram of a ‘one-chip’ ASIC solution, UZZ9000.

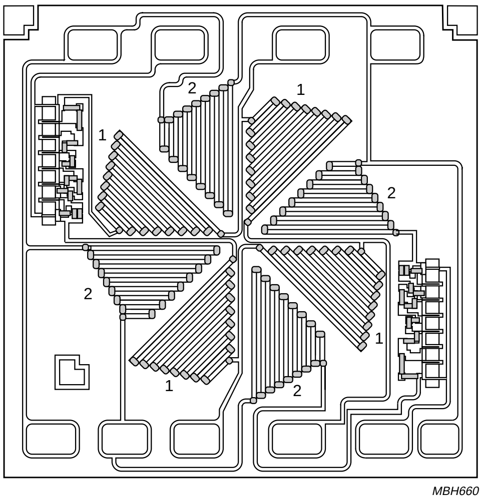

Fig.7 Layout KMZ41 chip.

Figure 7 shows the actual layout of Philips KMZ41. It has provides 8 MR resistor networks, connected as two individual Wheatstone bridges, aligned with a 45° shift in their sensitive magnetic directions, producing the required 90° electrical shift.

Of course, it is also possible align both bridges magnetically parallel to each other so they produce the same output signal. In that case, redundancy is achieved using a single sensor device. By increasing the number of bridges, a combination of both principles can be achieved to make, for example, a three-times redundant sensor or a fully redundant sensor that can measure over the full 90°, or any combination.

### Philips sensor modules for angle measurement

Based on magnetoresistive sensors, Philips Semiconductors has developed a range of ready-to-use magnetoresistive sensor modules for contactless angle measurement offering the following features:

- Offset, zero point and sensitivity are pre-trimmed (so assembly of the final encapsulated sensor is simple and calibration after assembly is unnecessary)
- Integrated temperature compensation; and
- EMC protection.

These ready-to-use modules with built in signal conditioning electronics have several advantages:

- Output is independent of magnet tolerances, temperature coefficients, mechanical set-up and other tolerances
- A single linear output signal can be provided for angles up to 180°
- A variety of output signals can be provided: analog (voltage or current), Pulse Width Modulation (PWM) and bus interfaces (e.g. I$^2$C, CAN).

Philips' KM110BH/2xxx family is a range of modules using hybrid thick-film technology. The circuits and magnetic parameters of these modules have been designed so they can be used directly in many applications, with no further trimming or adjustment, as the basis for customized solutions.

To reduce system costs and simplify application even further, a family of ASIC solutions is in development, some of which contain both sensor and conditioning electronics. By combining both elements in a single encapsulation, pre-aligned systems can be offered which can be simply mounted on a normal PCB.

In addition to the ready-made modules, Philips Semiconductors is willing to undertake customised designs for high volume applications (in excess of 50,000 units), either as specific hybrid or integrated solutions.

### KMB110BH/21 MODULE SERIES

Figure 8 shows the construction of the KM110BH/21 module, which is based on the KMZ10B sensor and is available in two types: the KM110BH/2130 and KM110BH2190. They are both based on the same circuit, but are trimmed differently: the KM110BH/2130 is trimmed to a higher amplification and measures angles between –15° and +15°, generating a linear output signal; while the KM110BH/2190 measures angles from approximately –45° to +45° and produces a sinusoidal output. Both produce an analog voltage signal. Figure 9 shows the output $V_o$ of the two modules, as a function of the measured angle $\alpha$. For further details, refer to Table 1.

### KM110BH/2270 MODULE

The KM110BH/2270 module, which is based on the KMZ11B1 sensor, is trimmed to measure angles ranging from –35° to +35° and has integrated input voltage stabilization. In contrast to the other modules in the KM110BH/2 range, the KM110BH/2270 has an analog current output signal (4 to 20 mA), which can be converted to a voltage signal using a simple resistor. The output is sinusoidal. This module has extremely good resolution and reproducibility (better than 0.001° at $\alpha = 0°$) and hysteresis, which is typically 0.02° at a = 0°, is very low.

When designing an encapsulation for the KM110BH/2270, it may be necessary to have the pins of the hybrid bent into an ‘S’ shape, to avoid excessive force on the solder joints. In this case, please order the KM110BH/2270G. For further details, refer to Table 1.

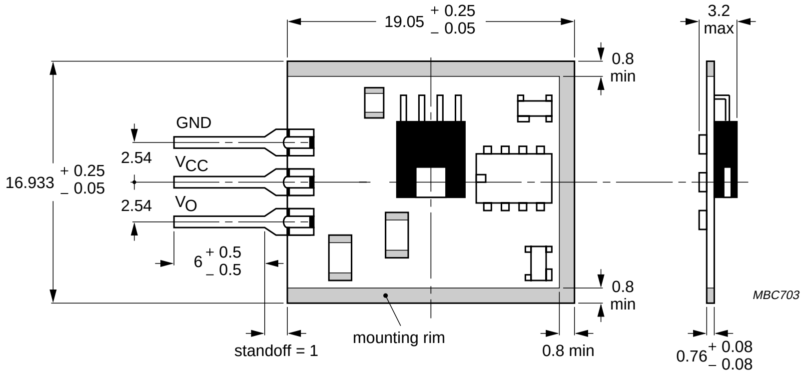

Fig.8 Construction of a KM110BH/21.

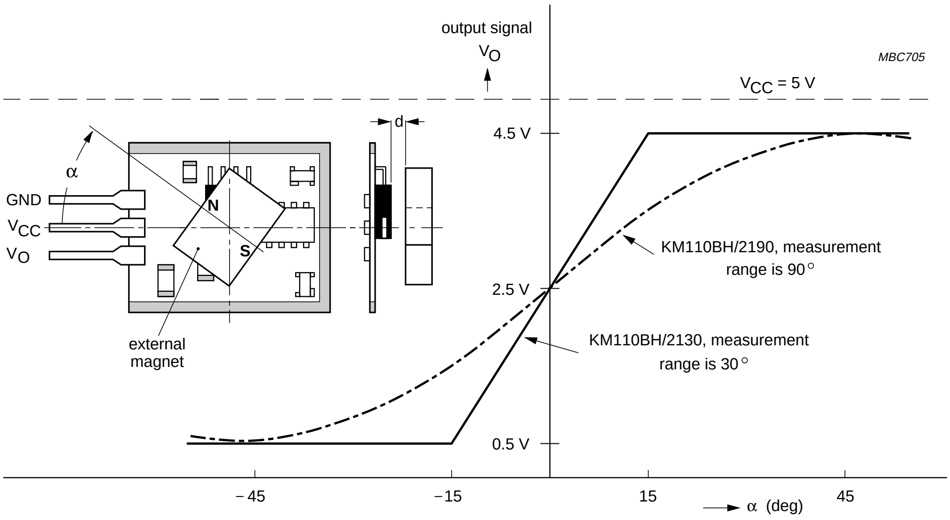

Fig.9 Output characteristics of the KM110BH/2130 and KM10BH/2190 modules.

**Table 1** An overview of the main characteristics of Philips modules for angle measurement

| PARAMETER | KM110BH | | | | | UNIT |
|---|---|---|---|---|---|---|
| | **2130**[1] | **2190**[2] | **2270** | **2430** | **2470** | |
| Angle range | 30 | 90 | 70 | 30 | 70 | deg |
| Output voltage[3] | 0.5 to 4.5 | 0.5 to 4.5 | – | 0.5 to 4.5 | 0.5 to 4.5 | V |
| Output current | – | – | 4 to 20 | – | – | mA |
| Output characteristic | linear | sinusoidal | sinusoidal | linear | sinusoidal | – |
| Supply voltage | 5 | 5 | 5 | 5 | 5 | V |
| Substrate dimensions | 9.1 × 16.9 | 9.1 × 16.9 | 23.6 × 20.3 | 23.6 × 20.3 | 23.6 × 20.3 | mm |
| Resolution | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | deg |
| Temperature range | –40 to +125 | –40 to +125 | –40 to +125 | –40 to +125 | –40 to +125 | °C |

KM110BH/24 MODULE

The KM110BH/24 is available in two versions based on the KMZ41: the KM110BH/2430 is trimmed to measure angles between –15° and +15°, generating a linear output signal (non-linearity is ≈1%); while the KM110BH/2490 measures angles from approximately –35° to +35° and produces a sinusoidal output. On-board protection circuitry makes these modules EMC tolerant.

### Real-life angular measurement applications

With angular measurement using magnetoresistive sensors, the number of possible applications is very broad, replacing and outperforming other types of sensors in a variety of applications, some of which are listed in Table 2:

Amongst these numerous applications, undoubtedly the most common is in the automotive industry, where they are used to measure pedal and throttle position.

REDUNDANT SYSTEMS

As multiple sensors with identical behaviour can be implemented on a single piece of silicon, a magnetoresistive set-up is an ideal solution for the construction of redundant systems, in safety critical applications, for example, such as a car accelerator pedal.

The essential functional blocks of a typical redundant sensor system are shown in Fig.10. For each sensor, the signal is first amplified. This stage also includes offset compensation and determines the characteristic of the output signal (sinusoidal or linear). After temperature compensation, the third stage provides additional trimming of the output signal and allows for the inclusion of diagnostic functions (for example, wire not connected or short circuit conditions). The final stage provides additional protection, against short circuits (between the supply voltage and the output signal, for example) or overvoltage (for example, if the 5 V module supply is accidentally connected to a 14 V battery supply).

**Table 2** Typical applications for angle sensors

| **Automotive and agricultural** | **Industrial** |
|---|---|
| • Pedal position<br>• Active suspension units<br>• Self-levelling systems<br>• Automatic headlight adjustment | • Valve control<br>• Material thickness<br>• Feedback systems for belt control<br>• Wear detection |
| **Medical** | **Consumer** |
| • Body and brain scanners where accurate angle information is vital to build up cross-sectional images<br>• Control joysticks for tilting tables | • Games joysticks<br>• Spirit levels |

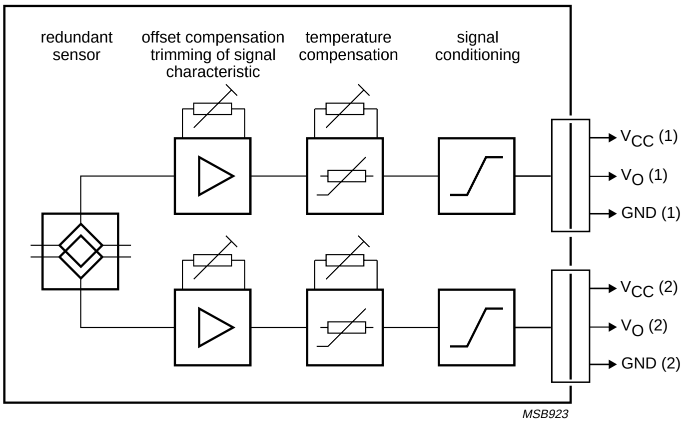

Fig.10 Functional block diagram of module with redundancy.

## Information for advanced users and applications

### Additional measurement set-ups

### *Linear*

In linear angle measurement, the strength of the external magnetic field used is within normal sensitivity levels and the sensor measures the resulting field strength of the rotating magnet. As can be seen from Fig.11, the signal linearity of a weak field method allows for angles up to ±90° to be measured without correction for the sinusoidal shape of the wave. This is the technique used in most competing angle measurement set-ups. However, since the magnet's properties directly influence sensor output, the measurement equipment must be carefully calibrated after it is assembled and calibration for material ageing is not possible at all. Only with a very well defined magnetic system can a pre-calibrated circuit be used and defining such a system is difficult and expensive, due to the tolerances caused by the thermal sensitivity of the magnet and the mechanical set-up.

By using a set-up with two magnets placed on a rotatable frame, angular rotations of around ±85° can be measured and through the symmetrical positioning of the magnets, the effect of the magnet position is eliminated. Figure 12 shows a practical arrangement, which basically acts as a contactless potentiometer. However, the response is not a perfectly sinusoidal due to magnetic influences on the ‘x’ and ‘y’ axis.

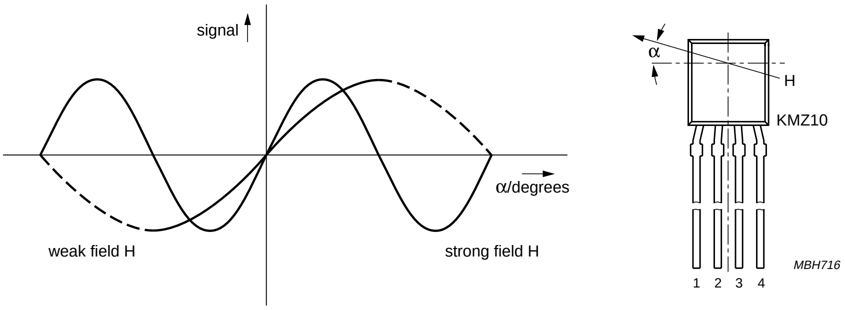

Fig.11 Sensor response for different magnetic fields.

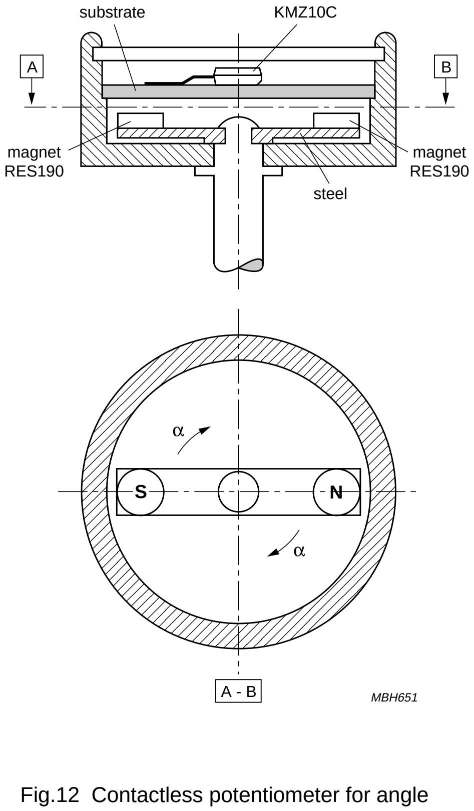

Fig.12 Contactless potentiometer for angle measurement.

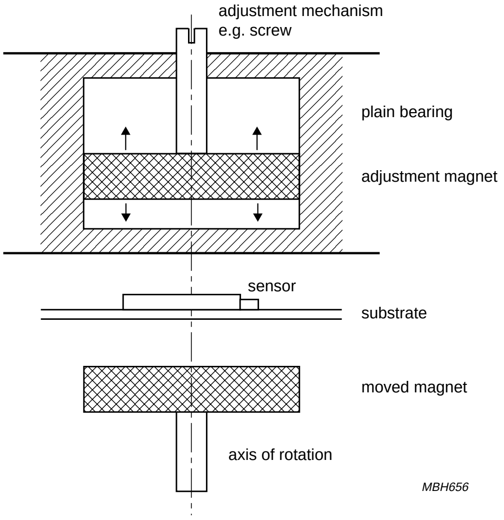

Fig.13 Angle sensor with adjustable measuring range.

*Extending measurement angle to greater than 90°*

With a second fixed magnet, it is possible to adjust the sensing distance and the angle range can be further extended, to cope with angles greater than ±90°. This can lead to increased mechanical tolerances although by using magnets of the same material, temperature variations can be disregarded. Figure 13 shows a typical set-up.

### MAGNETS

The main requirement for the magnet is that it should be strong, to ensure all tolerances are negligible, but obviously cost and space must also be considered, according to individual application requirements. Table 3 compares three commercially available Samarium-Cobalt (SmCo) magnets suitable for angle measurement applications.

These magnets have a tolerance in their magnetization direction which affects angle measurement. This tolerance, which can be up to 2%, should be taken into account if no mechanical calibration is possible at $\alpha = 0°$.

The symmetry axis of the module and the rotation axis of the magnet should be identical, although if one of the axes is shifted slightly, the affect on sensing accuracy can be neglected because the field lines of the magnet are parallel. Measurements with magnets with a face of 11.2 × 8 mm oriented towards the sensor allow for eccentric tolerances of up to 0.5 mm, assuming an acceptable tolerance in $V_o$ of 1%; and up to 0.25 mm, for an acceptable tolerance in $V_o$ of 0.5%. Evidently, if the magnet is smaller, these values should be proportionately reduced.

**Table 3** Typical values for various dimensions of $Sm_2Co_{17}$ magnets

| MATERIAL | DIMENSIONS[(1)] (mm) | d[(2)] (mm) | TOLERANCE d[(3)] (mm) | ECCENTRICITY[(4)] (mm) | $T_{amb}$ (°C) |
|---|---|---|---|---|---|
| $Sm_2Co_{17}$ | 11.2 × 5.5 × 8 | 2.1 | ±0.30 | ±0.25 | –55 to + 125 |
| | 6 × 3 × 5 | 0.7 | ±0.15 | ±0.15 | |
| | 8 × 3 × 5 | 0.5 | ±0.30 | ±0.20 | |

**Notes**

1. Magnetization is always parallel to the latter dimension.
2. d' is the distance between the magnet and the front of the sensor.
3. Tolerance' is the maximum deviation in 'd' for which the change in sensor output signal is <0.5% of full scale output.
4. Eccentricity' is the maximum deviation of the magnet rotational axis from the sensor rotational axis for which the change in sensor output signal is <0.5% of full scale output.

### ANGLE SENSOR ECCENTRICITY

In angle measurement using the direct measurement technique, the ideal arrangement is with a homogeneous parallel field. Although large magnets fulfil this requirement, there is usually a compromise between magnet size and the corresponding tolerances of the sensor due to cost considerations.

If the sensor and the magnet rotation axes are in line, the sensor output characteristics follow approximately the following signal voltage relationship:

$V_o = V_o(0) \times \sin 2\alpha$

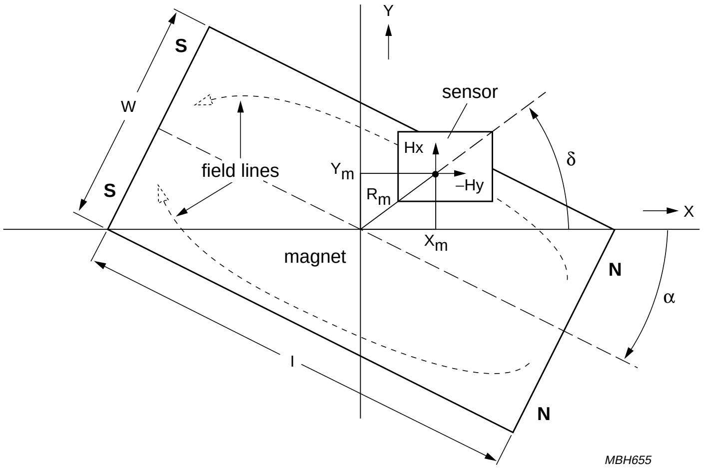

Fig.14 Angle sensor with eccentric sensor position.

However, depending on the sensor position in relation to the magnet and the angle to be measured (see Fig.14), offsets or sensitivity changes can occur. These conditions alter the ideal relationship as described by the equation above.Angle tolerance values can be calculated using the following relationship:

$\Delta\alpha = C \times R_m^2 \times \sin 2(\alpha + \delta)$

C is a magnetic constant and, provided the width and length of the magnet are approximately equal, can be calculated from the following equation:

$$C = \frac{320}{(w + l)^2}$$

**Table 4** Typical values of C for $Sm_2Co_{17}$ magnets

| **MAGNET DIMENSIONS (w × h × l, mm)** | **C (degree/mm$^2$)** |
|---|---|
| 6 × 3 × 5 | 2.6 |
| 8 × 3 × 7.5 | 1.35 |
| 11.2 × 5 × 8 | 0.74 |

For positions on the x- and y-axis, there is a sensitivity change with a maximum tolerance level at α = ±45° and ±135° (see Fig.15); for diagonal positions, an offset tolerance occurs with a maximum at α = ±90° and ±180° (see Fig.16).

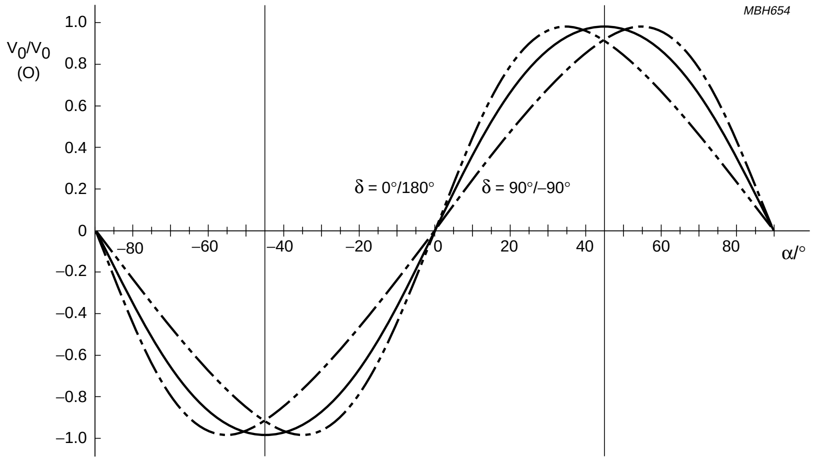

Fig.15 Response tolerances for sensor position on x- and y-axes.

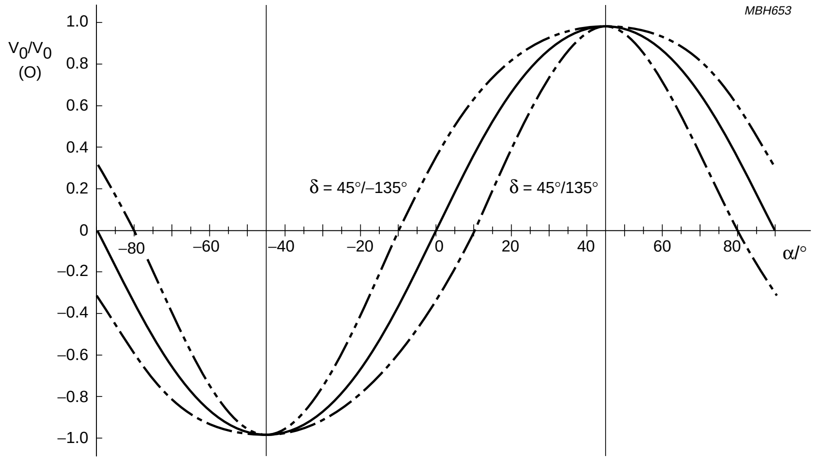

Fig.16 Response tolerances for sensor position diagonals.

**Table 5** Typical tolerance values of $|\Delta\alpha|$ for $C \times R_m^2 = 1$

| **Δ (DEGREES)** | **\|Δα\| (DEGREES)** | | | |
|---|---|---|---|---|
| | **0** | **15** | **30** | **45** |
| 0/90/... | 0 | 0.5 | 0.87 | 1 |
| 45/135/... | 0 | 0.134 | 0.25 | 1 |

*Single sensor system*

If we assume that a single, encapsulated angle sensor with eccentricity will be adjusted mechanically to the specified output voltage $V_o(\alpha = 0)$, then the tolerances at $\alpha = 0$ are set to zero. Then over the useful angle range of ±45°, the original offset tolerances can be transformed into a resultant $|\Delta\alpha|$ tolerance:

$$|\Delta\alpha| = 2C \times R_m^2 \sin^2\alpha$$

Some typical values when $C \times R_m^2 = 1$ are shown in Table 5.

An adjusted 30° angle sensor has a maximum tolerance of:

$$|\Delta\alpha| = \tfrac{1}{2} C R_m^2 \text{ at } \pm 15°$$

and in the range between 0° and 15°, the tolerance increases approximately linearly from zero to this value. Above ±15° the sinusoidal function given above is effective and has to be taken into account for the 70° and 90° sensors.

Figure 17 gives the maximum tolerances at $\alpha = \pm 15°$ for different magnets as a function of the eccentricity radius $R_m$.

In general, the tolerance is about 0.3° or 1% FS, provided $R_m$ corresponds to about 10% of the magnetic dimensions l and w.

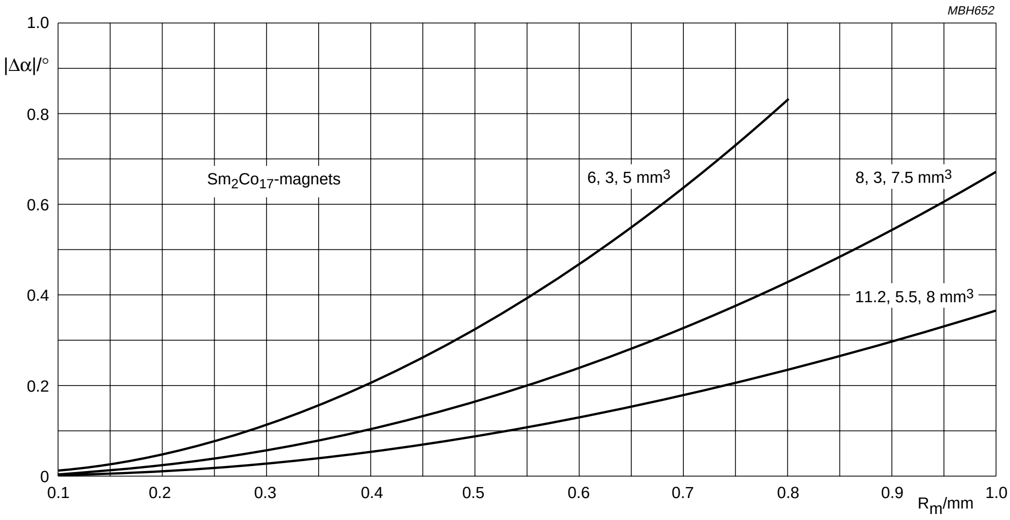

Fig.17 Maximum angle tolerances Δα.

*Double sensor system (KMZ41)*

In this case, both sensors are influenced differently and the resulting tolerance Δα has to be calculated from the deviations of the two response curves. If C.Rm2 is sufficiently small, and the angle a is calculated from the relation of the two output signals via the arc-tan function, then the resulting measuring tolerance can be described by:

$|\Delta\alpha| = C \times R_m^2 \times \cos 4\alpha \times \sin 2(\alpha + \delta)$

This leads to the worst case tolerance of $|\Delta\alpha| = C \times R_m^2$ occurring at $\alpha$ = 0°, 45° and 90° and a tolerance of zero at $\alpha$ = 22.5°, 67.5° and 112.5°. These zero positions can be used to adjust the sensor for the highest precision measurements.

If the sensors are adjusted in this way, the maximum tolerance is limited to $C \times R_m^2$.

SUNSTAR 商斯达实业集团是集研发、生产、工程、销售、代理经销 、技术咨询、信息服务等为一体的高科技企业，是专业高科技电子产品生产厂家，是具有 10 多年历史的专业电子元器件供应商，是中国最早和最大的仓储式连锁规模经营大型综合电子零部件代理分销商之一,是一家专业代理和分銷世界各大品牌 IC 芯片和電子元器件的连锁经营綜合性国际公司，专业经营进口、国产名厂名牌电子元件，型号、种类齐全。在香港、北京、深圳、上海、西安、成都等全国主要电子市场设有直属分公司和产品展示展销窗口门市部专卖店及代理分销商,已在全国范围内建成强大统一的供货和代理分销网络。 我们专业代理经销、开发生产电子元器件、集成电路、传感器、微波光电元器件、工控机/DOC/DOM 电子盘、专用电路、单片机开发、MCU/DSP/ARM/FPGA 软件硬件、二极管、三极管、模块等，是您可靠的一站式现货配套供应商、方案提供商、部件功能模块开发配套商。商斯达实业公司拥有庞大的资料库，有数位毕业于著名高校——有中国电子工业摇篮之称的西安电子科技大学（西军电）并长期从事国防尖端科技研究的高级工程师为您精挑细选、量身订做各种高科技电子元器件，并解决各种技术问题。

微波光电部专业代理经销高频、微波、光纤、光电元器件、组件、部件、模块、整机；电磁兼容元器件、材料、设备；微波 CAD、EDA 软件、开发测试仿真工具；微波、光纤仪器仪表。欢迎国外高科技微波、光纤厂商将优秀产品介绍到中国、共同开拓市场。长期大量现货专业批发高频、微波、卫星、光纤、电视、CATV 器件： 晶振、VCO、连接器、PIN 开关、变容二极管、开关二极管、低噪晶体管、功率电阻及电容、放大器、功率管、MMIC、混频器、耦合器、功分器、振荡器、合成器、衰减器、滤波器、隔离器、环行器、移相器、调制解调器；光电子元器件和组件：红外发射管、红外接收管、光电开关、光敏管、发光二极管和发光二极管组件、半导体激光二极管和激光器组件、光电探测器和光接收组件、光发射接收模块、光纤激光器和光放大器、光调制器、光开关、DWDM 用光发射和接收器件、用户接入系统光光收发器件与模块、光纤连接器、光纤跳线/尾纤、光衰减器、光纤适 配器、光隔离器、光耦合器、光环行器、光复用器/转换器；无线收发芯片和模组、蓝牙芯片和模组。

更多产品请看本公司产品专用销售网站:
商斯达中国传感器科技信息网：http://www.sensor-ic.com/
商斯达工控安防网：http://www.pc-ps.net/
商斯达电子元器件网：http://www.sunstare.com/
商斯达微波光电产品网:HTTP://www.rfoe.net/
商斯达消费电子产品网://www.icasic.com/
商斯达实业科技产品网://www.sunstars.cn/ 微波元器件销售热线：
地址：深圳市福田区福华路福庆街鸿图大厦 1602 室
电话：0755-82884100 83397033 83396822 83398585
传真：0755-83376182 （0）13823648918 MSN: SUNS8888@hotmail.com
邮编：518033 E-mail:szss20@163.com QQ: 195847376
深圳赛格展销部：深圳华强北路赛格电子市场 2583 号 电话：0755-83665529 25059422
技术支持: 0755-83394033 13501568376

欢迎索取免费详细资料、设计指南和光盘 ；产品凡多，未能尽录，欢迎来电查询。

北京分公司：北京海淀区知春路 132 号中发电子大厦 3097 号
TEL：010-81159046 82615020 13501189838 FAX：010-62543996
上海分公司：上海市北京东路 668 号上海赛格电子市场 D125 号
TEL：021-28311762 56703037 13701955389 FAX：021-56703037
西安分公司：西安高新开发区 20 所(中国电子科技集团导航技术研究所)
西安劳动南路 88 号电子商城二楼 D23 号
TEL：029-81022619 13072977981 FAX:029-88789382