6.6 Application Notes: Differential Hall IC TLE 4921-3U

Applications

- Detection of rotational speed of ferromagnetic gear wheels
- Detection of rotational position
- Detection of rotational speed of magnetic encoder wheels
- Generation of trigger signals

Main Features

- Evaluation of very small magnetic field differences
- Large airgap in dynamic mode
- Low cut-off frequency
- Fully temperature compensated
- Clean, fast, bounce-free switching
- Overvoltage and reverse polarity protection
- Guarded against RF interference
- Wide temperature range
- Open-collector output

General Description

The TLE 4921-3U has a combination of two Hall cells, a differential amplifier and evaluating circuitry, all on a single chip. Evaluating field difference instead of absolute field strength means that disruptive effects, like temperature drifts, manufacturing tolerances and magnetic environment are minimized. Further reduction in interference is obtained by the dynamic evaluation of the difference signal using a highpass filter with an external capacitor.

The IC is designed for use under aggressive conditions found in automotive applications. A small permanent biasing magnet is required for sensing ferromagnetic gear wheels of various shapes. Correct switching for even the smallest field differences between tooth and gap is guaranteed. The typical lower switching frequency is about 10 Hz for a 470 nF filter capacitor. The TLE 4921-3U is offered in a 1 mm thick ultraflat package with four leads (P-SSO-4-1).

Design and Function of the Chip

When the Hall IC is exposed to a constant magnetic field of either polarity, the two Hall elements will produce the same output signal. The difference is zero, regardless of the absolute field strength. However, if there is a field gradient from one Hall element to the other, because one element faces a field concentrating tooth and the other one a gap of the toothed wheel, then a difference signal is generated. This signal is amplified on the chip. In reality the difference exhibits a small offset which is corrected by the integrated control mechanism. The dynamic differential principle allows a high sensitivity in combination with large airgaps between the sensor surface and the gear wheel.

A Schmitt Trigger is used to digitize the conditioned signal. An open-collector output with current sinking capability provides the output signal. Protection against overvoltage and reverse polarity as well as against EMI are integrated and allow application in the hostile environments found in the automotive industry.

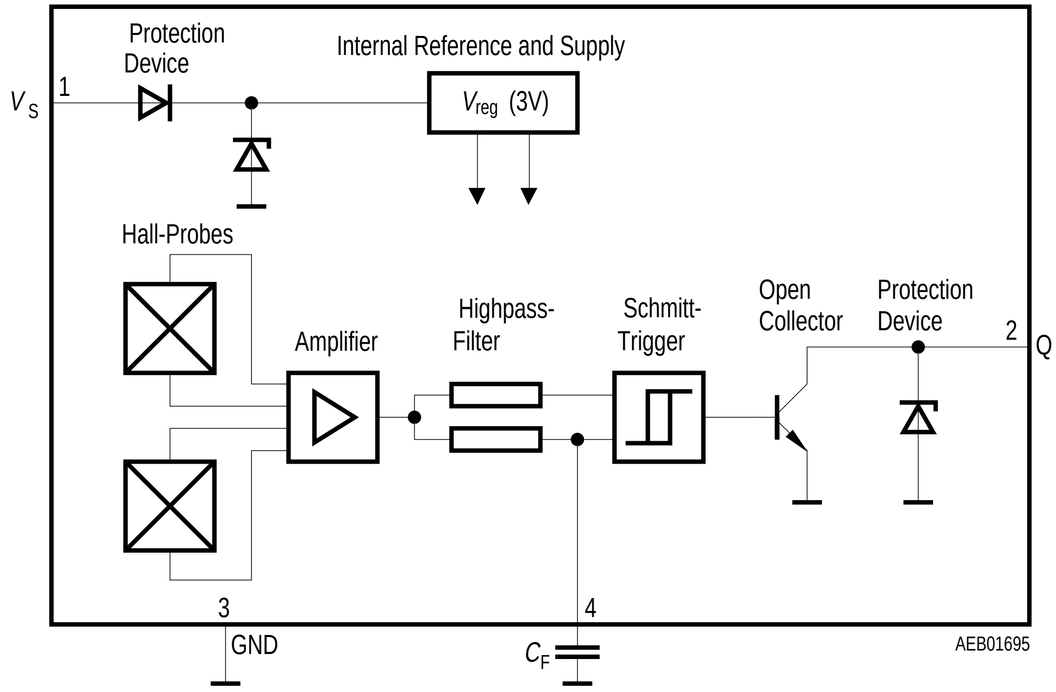


Figure 60
Block Diagram TLE 4921-3U

Method of Operation

The generation and evaluation of the difference signal can be explained with reference to a typical application such as sensing a ferromagnetic gear wheel.

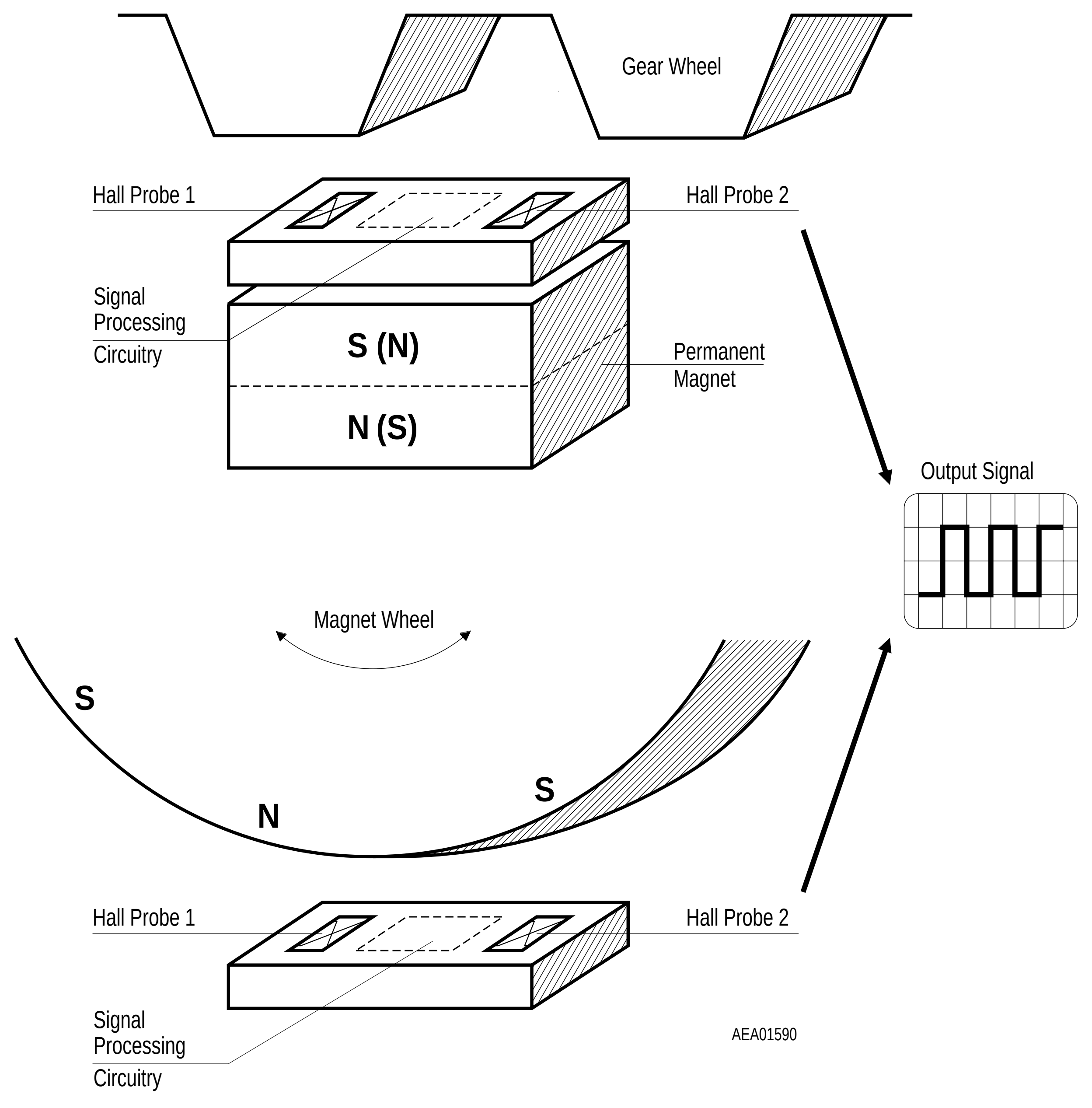
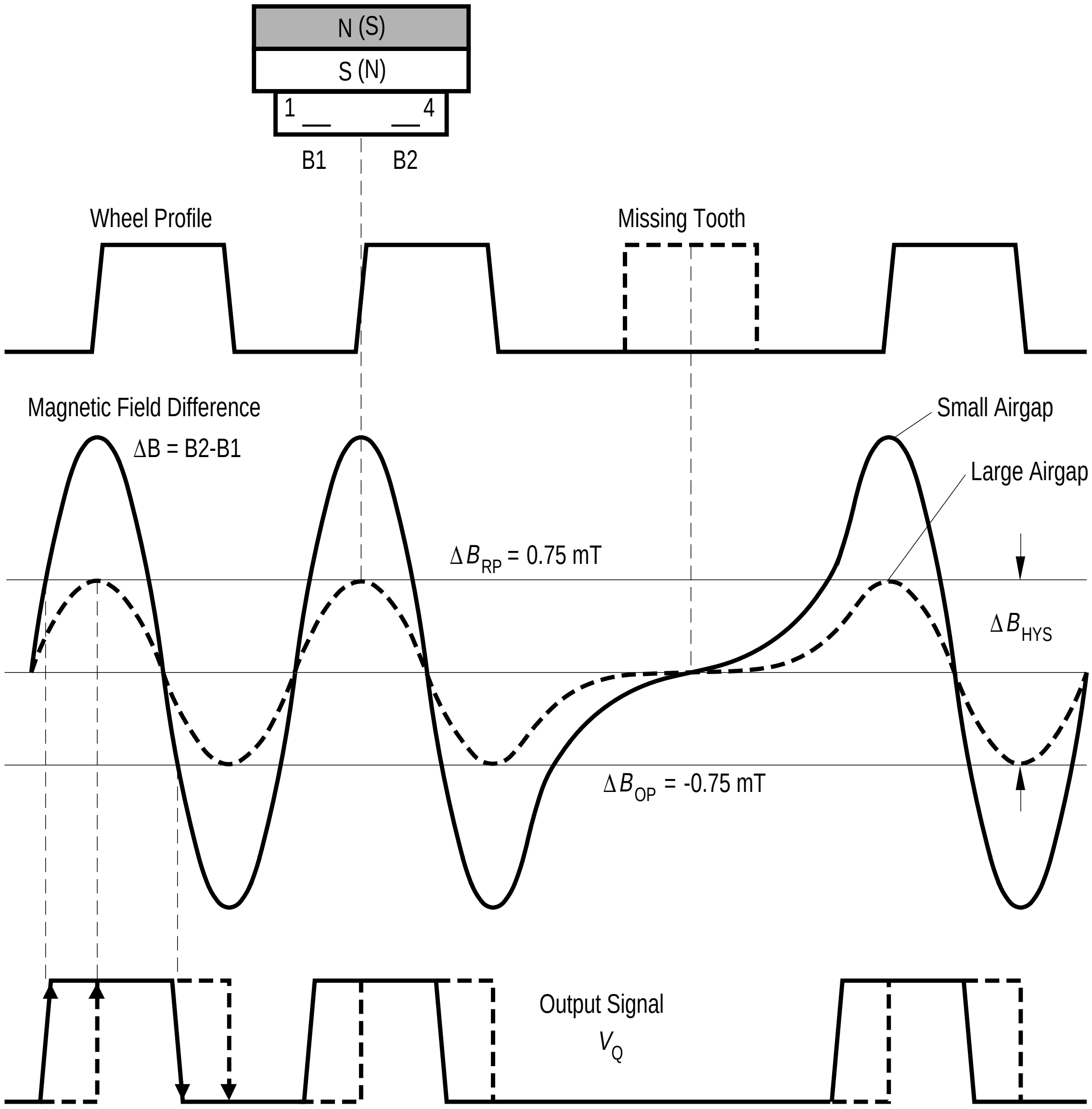


Figure 61
Application as a Gear Wheel Sensor and as an Encoder Wheel Sensor

A permanent magnet mounted with either pole on the rear side of the IC produces a constant magnetic bias field. The two Hall probes are spaced at 2.5 mm. If one cell faces momentarily a tooth while the other faces a gap of the toothed wheel, the gear tooth acts as a flux concentrator. It increases the flux density through the Hall probe and a differential signal is produced. As the toothed gear wheel turns, the differential signal changes its polarity at the same rate of change as from the tooth to the gap.

The maximum difference is produced by the tooth edge when the zero crossover comes directly in the center of the tooth or gap. When the difference exceeds the upper threshold ΔB_{RP}, the output transistor of the TLE 4921-3U will turn OFF (V_{Q} = HIGH).This is the case when the tooth is sensed by the Hall probe 2 near pin 4 in **Figure 61**. As the difference falls below the lower threshold ΔB_{OP}, the transistor turns ON (V_{Q} = LOW). This is the case when the Hall probe 1 near pin 1 senses the tooth.

The integrated highpass filter regulates the difference signal to zero by means of a time constant that can be set with an external capacitor. In this way only those differences are evaluated that change at a minimum rate (depending on the capacitor value). The output signal is not defined in the steady state. The accuracy that is produced will permit a small switching hysteresis and therefore also a large airgap (up to 3.5 mm).



Operate point : B2 - B1 < ΔB_{OP} switches the output ON (V_Q = LOW)
Release point : B2 - B1 > ΔB_{RP} switches the output OFF (V_Q = HIGH)
$\Delta B_{RP} = \Delta B_{OP} + \Delta B_{HYS}$

The magnetic field is defined as positive if the south pole of the magnet shows towards the rear side of the IC housing.

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Figure 62
Sensor Signals Produced by a Toothed Gear Wheel

Gear Wheel, Sensing Distance and Angular Accuracy

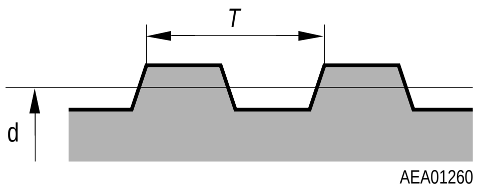
A gear wheel is characterized by its modulus:

$$m = \frac{d}{z}$$

d: pitch diameter

z: number of teeth

The space T from tooth to tooth, the pitch, is calculated by the formula $T = \pi \cdot m$



Conversion DIN – ASA

$m = 25.4$ mm/p

$T = 25.4$ mm CP

DIN		ASA	
d	diameter (mm)	p	diameter pitch $p = z/d$ (inch)
z	number of teeth	PD	pitch diameter PD $= z/p$ (inch)
m	module $m = d/z$ (mm)	CP	circular pitch CP = 1 inch $\times \pi/p$
T	pitch $T = \pi \times m$ (mm)		

Figure 63
Toothed Wheel Dimensions

The difference in induction is at its greatest when one Hall element faces a tooth and the other one a gap. The spacing between the Hall elements on the IC is 2.5 mm, so the IC can detect a difference from the modulus 1 upwards, the corresponding pitch being 3.14 mm. If the modulus is much greater than 3, or the wheels are irregular, there is a risk of insufficient difference in induction over a longer period, meaning that the output signal will be nondefined.

The maximum possible distance between the sensor and the gear wheel – as a function of temperature, the modulus, the magnet and the speed – will be characterized by the fact that just one impulse manages to appear at the output for each tooth/gap transition.

The following measurements are made with different magnet types:

Table 14

Magnetic Type	**SmCo$_5$**	**Sm$_2$Co$_{17}$**	**NdFeB**	**NdFeB**
Size (in mm)	5 × 4 × 2.5	6 × 3 × 5	ø 5 × 3	ø 7.9 × 2
B at d = 0.5 mm (in mT)	250	300	280	230

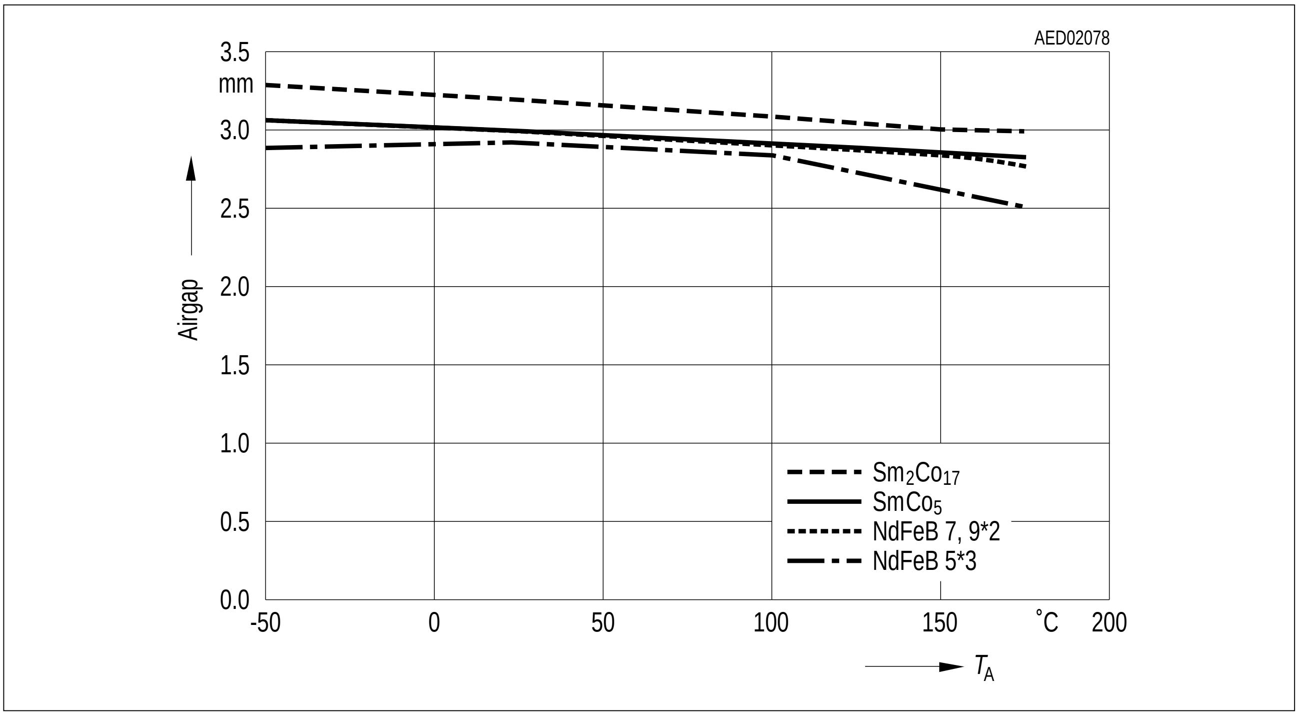


Figure 64
Maximum Sensing Distance for a Gear Wheel with Modulus 1,5 as a Function of Biasing Magnet

If the distance is reduced, a larger useful signal is produced. Therefore the switching accuracy increases with which a Low/High transition of the sensor can represent an angle of rotation of the gear wheel.

Filter Capacitor

The filter capacitor C_F plays an important role in the correct function of the Hall IC. If an application requires operating temperatures higher than 100 °C, ceramic capacitor types (X7R) are recommended. The connections between the filter capacitor C_F, the C pin and the GND pin need to be as short as possible. Further recommendations are listed in one of the following subsections.

A leakage current at the capacitor pin will cause a shift of the switching thresholds and therefore spurious switching. The shift of the switching threshold is calculated as

$$\Delta B_{\mathrm{m}} = \frac{I_{\mathrm{L}} \times R_{\mathrm{C}}(T)}{S_{\mathrm{C}}(T)}$$

where I_L, S_C and R_C are the leakage current, the filter sensitivity to ΔB and the filter input resistance as specified in the datasheet respectively.

Special attention has to be paid to the choice of the capacitor (high DC resistance) and its assembly. Leakage currents may occur on the PCB between the connections or in a defective capacitor and can be a source of sensor malfunction.

EMC: Injection of supply line transients (DIN 40839-1 and -2)

For the measurements with the TLE 4921-3U the test circuit shown in **Figure 65** is used. The filter capacitor C_F = 470 nF is connected directly to pin 4, additionally a shunt capacitor C_S = 4.7 nF is placed in the supply line. A serial resistance of 300 Ω is used (400 Ω for test pulse 5). Some applications do not allow such a high serial resistance, because it causes an undesired supply voltage drop. With a smaller serial resistance in the range of 50 – 150 Ω the following results are almost not affected, except the ones of pulse 5. Due to its long duration up to 400 ms this so-called load dump pulse generates high power levels to be dissipated in the Hall IC. Without a sufficiently large serial resistor the IC would be destroyed. Therefore the minimum resistor size must be adapted to the load dump requirements of the application or vice versa. Optionally a suppressor diode can be placed in the supply line, eliminating the need for a large serial resistor.

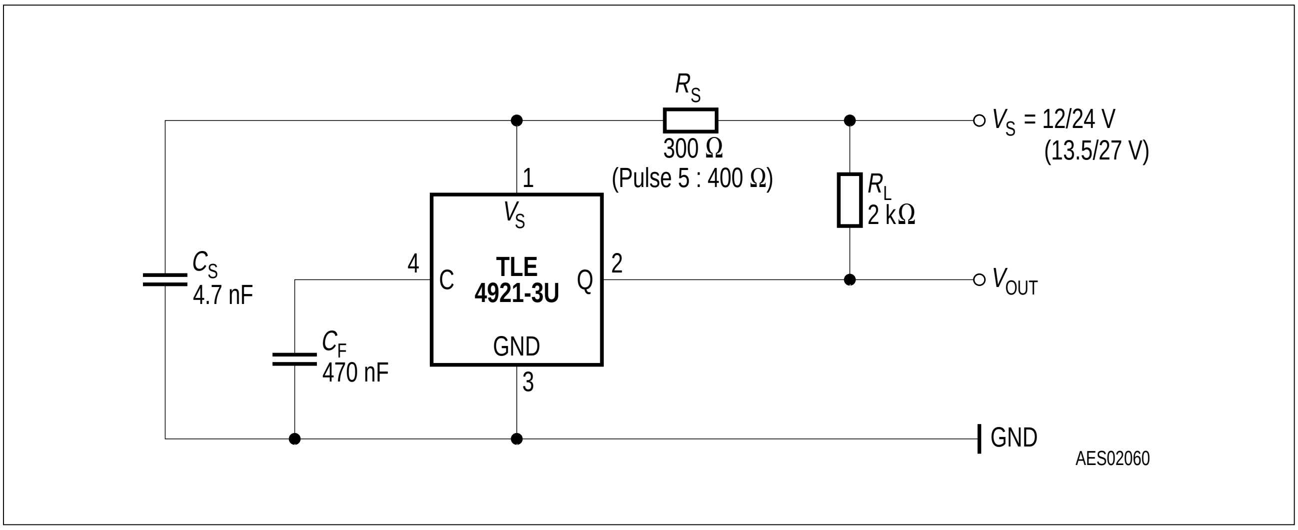


Figure 65
Circuitry for DIN 40839-1/-2 Test

The results obtained with the TLE 4921-3U are summarized in **Table 15**. The values in parenthesis apply for 24 V battery voltage operation. Detailed results of the measurements are available on request.

Table 15
Functional Status of TLE 4921-3U according to DIN 40839-1/-2 Test Levels

Test Pulse	**Functional Status according to Test Levels**				
	I	**II**	**III**	**IV**	
1	C (C)	C (C)	C (C)	C (C)	
2	A (A)	B (B)	B (B)	B (B)	A/B: if t_2 = 60 µs
3a	C (C)	C (C)	C (C)	C (C)	
3b	A (A)	A (C)	C (C)	C (C)	
4	C (C)	C (C)	C (C)	C (C)	
5	B (C)	C (C)	C (C)	C (C/D)	D: if t_0 > 200 ms
6	C	C	C	C	
7	C	C	C	C	

EMC: Radiated Interference (DIN 40839-4)

This test is carried out in a TEM cell. The setup is described in **Chapter 6.4** (Electromagnetic Compatibility in Automotive Application).

The PC-board, onto which the sensor is mounted, is optimized according the circuit in the following subsection. The results of the TEM measurements with an optimized PCB board are shown in **Figure 66**. It is seen that over the whole frequency range the TLE 4921-3U performs without disturbance up to the maximum field of 160 V/m. More details on the TEM measurements are available on request.

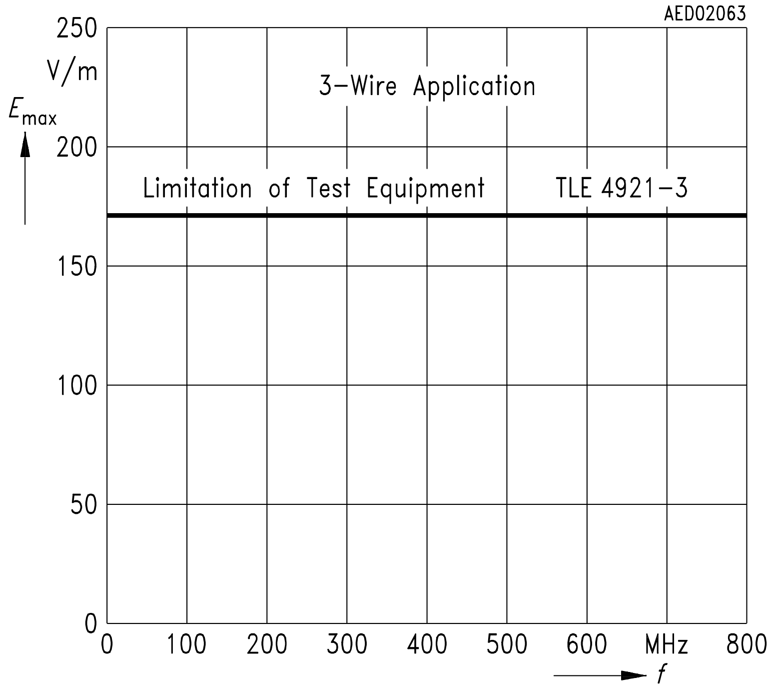


Figure 66
Results of the Radiated Interference Test with the TLE 4921-3U

Optimization of TLE 4921-3U PCB Layout for Improved EMI Performance, Three-wire Configuration

Due consideration of the PC-board layout is a prerequisite for optimized EMI performance of the TLE 4921-3U. The following recommendation is the result of EMI measurements carried out on the device during in-house testing.

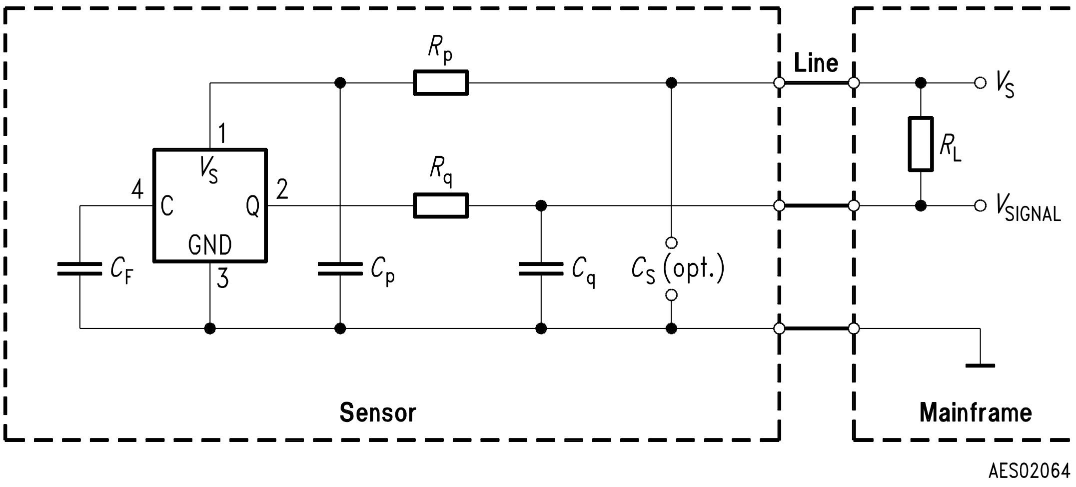


Figure 67
Optimized TLE 4921-3U PCB Circuit for Three-wire Operation

Component values:

C_F = 470 nF	High pass filter capacitor
C_S = 4.7 nF	Additional HF shunt (optional)
R_p = 0 – 330 Ω	Forms with C_p a low pass filter in the supply line
C_p = 4.7 nF	(against conductive coupling and fast interference pulses)
R_q = 33 Ω C_q = 4.7 nF	Serves with C_q to smoothen the falling edge of V_{SIGNAL}, i.e. reduction of irradiated interference
R_L = 330 Ω	Load resistor

Optimization points in detail:

1. Ground
   The reference point on the board is the GND pin of the device. In order to avoid conductive interferences, all connections to this pin should be realized in a star configuration. If this requirement is not fulfilled, the EM immunity will be reduced.
2. Connection of the filter capacitor
   The connections between the filter capacitor C_F, the C and GND pins have to be as short as possible (ideally C_F should be placed close to the device housing), taking into account the above mentioned star configuration of C_F to GND. If this is not possible, a second smaller capacitor (e.g. 82 nF) between C_F and TLE 4921-3U is recommended in order to shorten the connection between C_F and the corresponding pins. This measure should be applied only if little space is available close to the Hall IC.
3. Groundscreen
   In addition it is recommended to lay the GND connection of the filter capacitor out as a groundscreen for the connection of the capacitor to the C pin.
4. Additional RF shunts
   Ideally arranged RF shunts C_S can further improve the EMI immunity.

The effect of the above listed optimization steps (with decreasing significance) can vary according to the system (sensor, cable, control unit). Depending on the application, not all the measures need to be applied.

Detecting Speed of Rotation

The output signal of the gear-tooth-sensor is rectangular. Each alteration of the switching status represents a change from tooth to gap or vice versa. The duty cycle for a rectangular tooth-wheel (e.g. modulus 2) and sensing distance of 1 to 2 mm is virtually 1:1.

Depending on the application the speed information will be required in digital form or in analog form as a voltage.

Analog Evaluation

Speed control is the commonest task in classic control engineering. The controlled variable that is taken for an analog controller (P, PI, PID) is a voltage proportional to the speed. The first step in obtaining this speed proportional voltage is that the sensor output signal is converted into a rectangular signal fixed ON-time and a variable OFF-time, dependent on the speed, by an edge-triggered monoflop. In the second step the linear average is formed. This, using a conversion factor, is directly proportional to the speed.

$$V_{\text{analog}} = V_{\text{op}} \times \text{RC} \times \text{T/60} \times \text{rpm}$$

Operating voltage

Revolutions per minute

Set monoflop time

No. of teeth on wheel

A moving-coil meter is especially suitable for analog display of the speed. This is an ideal averager above a lower cut-off frequency of typically 10 Hz.

If the speed-proportional voltage is processed electrically, the average value can be formed by a lowpass filter.

Digital Evaluation

If the speed-proportional voltage is to be produced as a digital, numeric reading, or if there is a microcomputer available in the system as a digital controller, the speed can be computed very easily for these purposes.

The gear-wheel sensor is connected to the count input of a microcontroller (e.g. external input of timer 0 on an 8051). The speed is detected by counting the HIGH/LOW transitions of the sensor output in a defined time window T_{window}. By careful definition of this time window, the speed can be produced directly as an rpm figure without conversion.

$$\text{Speed[rpm]} = \frac{\text{Counted pulses}}{T_{\text{window}}} \qquad \text{with } T_{\text{window}}[\text{s}] = \frac{60}{\text{Number of teeth}}$$

Example: A gear wheel with 15 teeth requires a time window of 4 s.
If one pulse is counted in the time window, this will correspond to 1 rpm.
This is at the same time the finest resolution that is possible.

Because of the high operating frequency of the microcontroller however, it is bothersome to set long time windows. If you select a shorter time window, the count has to be multiplied by a correction factor in the ratio of the ideal to the real time window. The metering accuracy and resolution that are achieved can nevertheless only amount to this factor at the maximum.

Example: Gear wheel with 15 teeth time → window 4 s.
Real time window 40 ms → correction factor 100.
If one pulse is counted in the set time window, this will correspond to 100 rpm.
If none is counted, the display will be zero.
It is seen that the lower metering limit is determined by the choice of time window.

Detecting Sense of Rotation

With Logic

Detecting the sense of rotation is a very simple matter with two sensors. These sensors should be arranged on the circumference of the tooth wheel so that their output signals are offset 90 ° in phase. The switching sequence of the sensors is converted into a static directional signal by an edge-triggered D-flipflop, because one sensor will switch earlier than the other depending on the sense of rotation.

The output signal of the dynamic tooth-wheel sensor is only valid above a minimum speed, this also applying to the direction signal that is obtained. So when a gear wheel is braked and started again in the opposite direction, the output signals and the direction signal about the standstill point are not particularly reliable.

With Software

The switching sequence can also be evaluated by a microcontroller and software. The sensor signals are connected to two interrupt inputs. At the same time it is possible to monitor the lower cut-off frequency by software. The sensor signals are not evaluated if they go beyond the lower cut-off frequency.

The principle of detecting sense of rotation is illustred in **Figure 68**.

A proven application circuit for analog sensing of rotational speed and sense is shown in **Figure 69**.

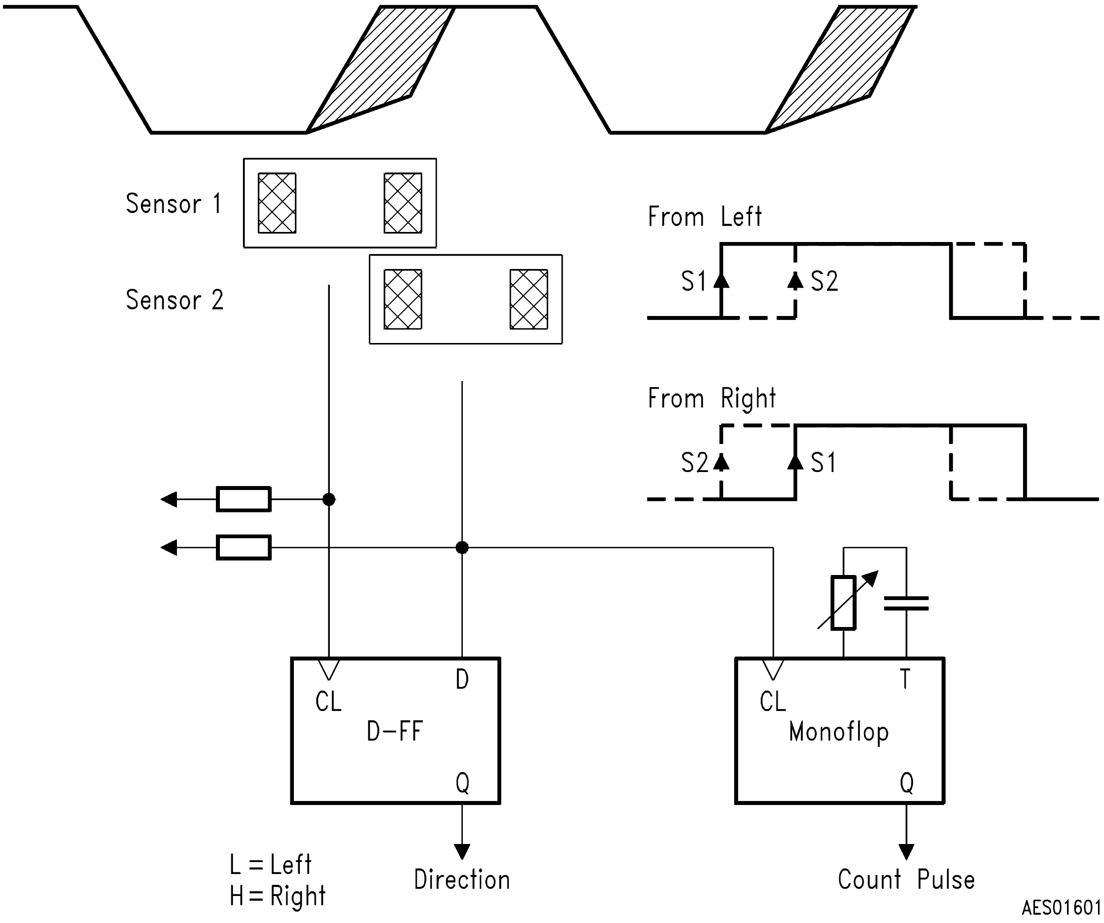


Figure 68
Detecting Sense of Rotation with Two Gear-Wheel Sensors

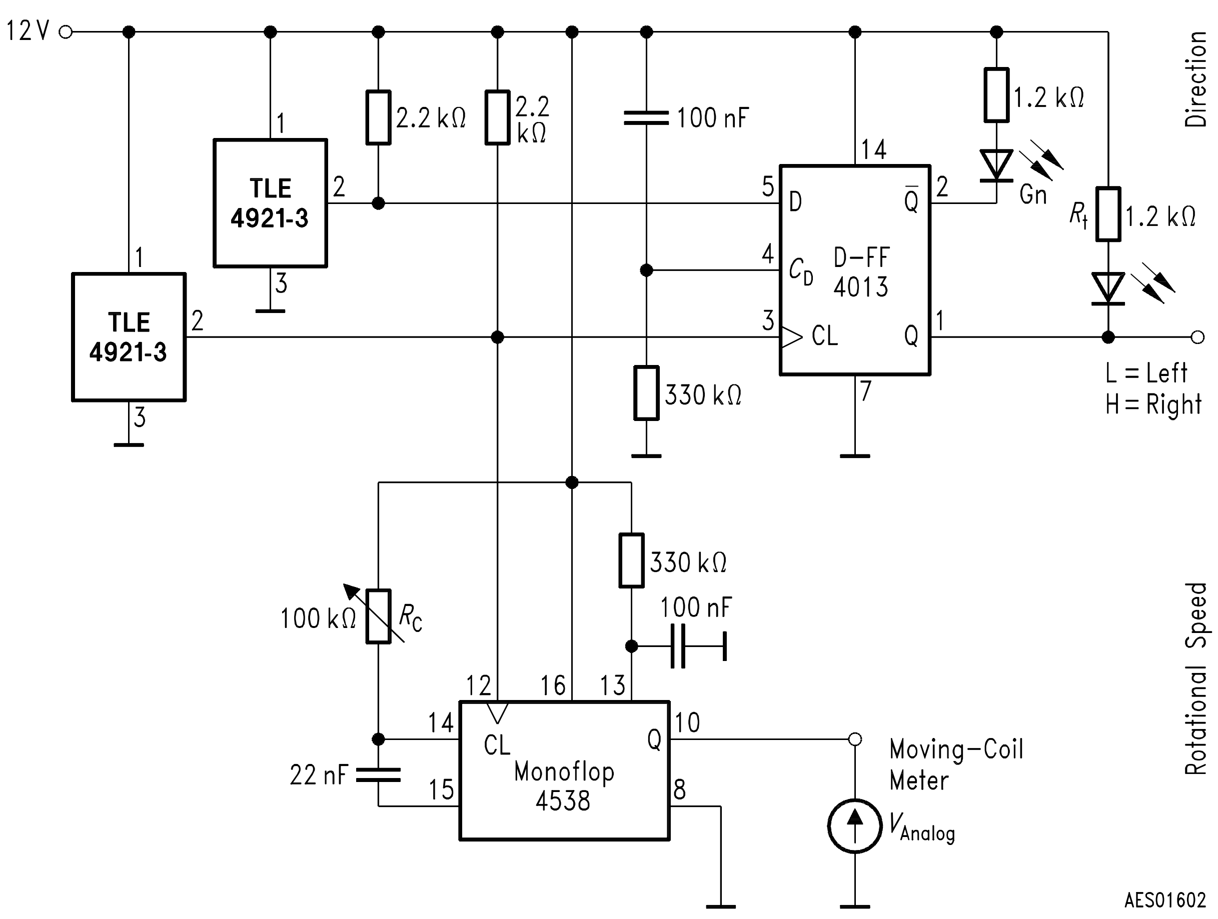


Figure 69
Application Circuit Rotational Speed/Rotational Sense

Signal Behaviour for different Dimensions of Toothed Gear Wheels

In order to give detailed information regarding to the signal behaviour for different gear tooth dimensions, the main points that influence the performance of a sensor/toothed wheel configuration are described below.

The following figures show the internal differential signal coming from two Hall elements, receiving a direct information on how the dimensions influence the performance.

The differential signal increases with the ferromagnetic mass and therefore with the tooth pitch T. If T is increased to more than 8 mm, the gradient becomes flat. Hence the optimum rating is then between 5 and 8 mm (**Figure 70**).

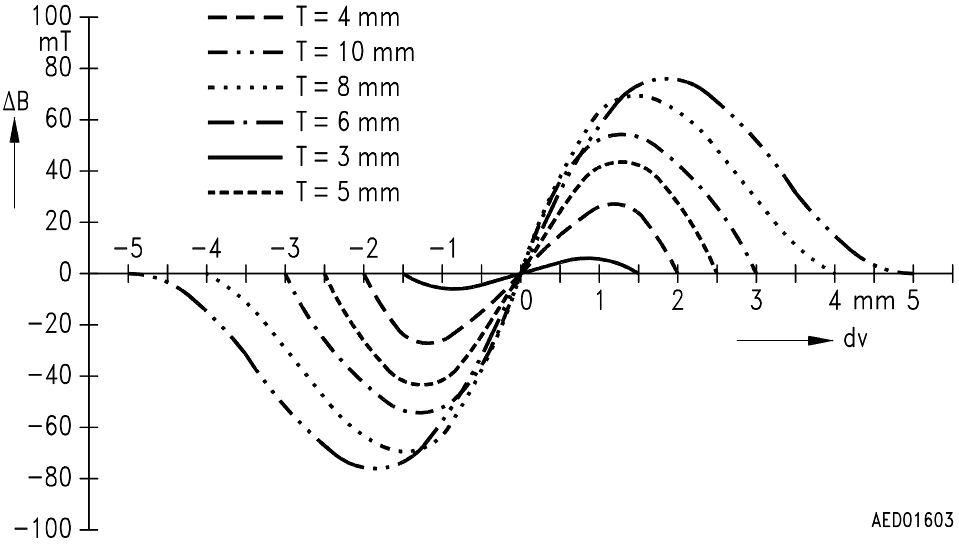


Figure 70
Differential Signal as a Function of Pitch T

According to the definition the position dv = 0 mm is where the tooth of the wheel is centered over the IC. Therefore at this position the differential signal is 0 (both Hall elements are influenced by the same magnetic flux). At the position where one Hall element faces a gap and the second element faces a tooth, the differential field has a maximum (dv = 1.25 mm). If T equals 5 mm then the differential signal is sinusoidal because the distance between the sensors is 2.5 mm = T/2 (see **Figure 71**).

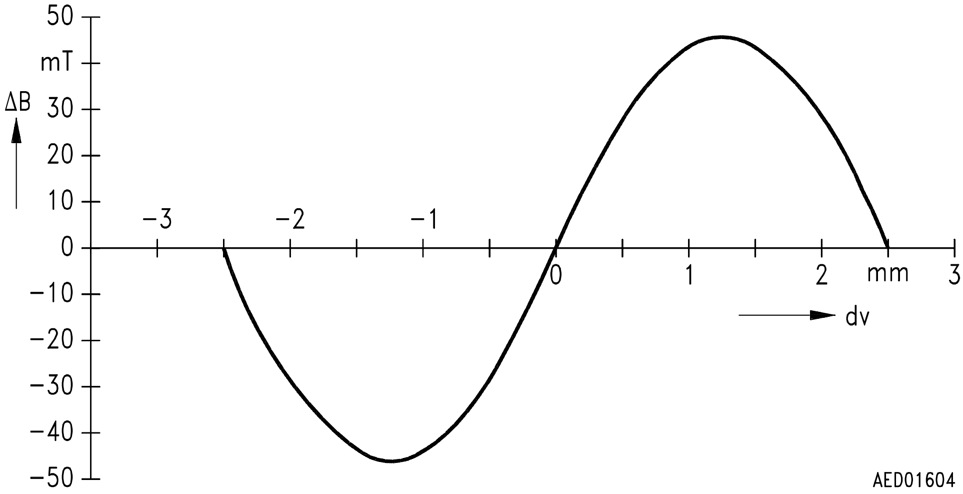


Figure 71
Differential Signal for a Pitch T = 5 mm

If T/2 is smaller than 2.5 mm, the influence of the gaps decreases and the Hall elements already detect the next tooth (**Figure 72**).

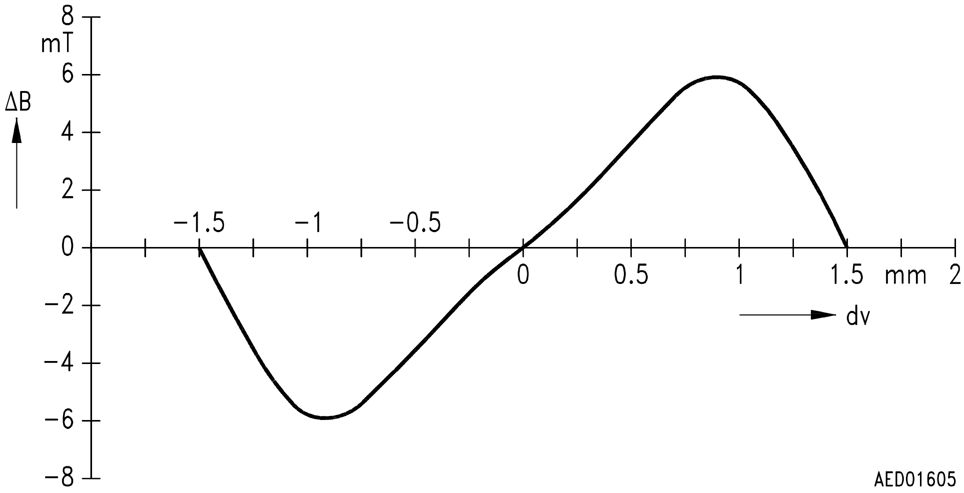


Figure 72
Differential Signal for a Pitch T = 3 mm

If T/2 is larger than 2.5 mm, the influence of the gaps increases and the Hall elements do not detect the next tooth (**Figure 73**).

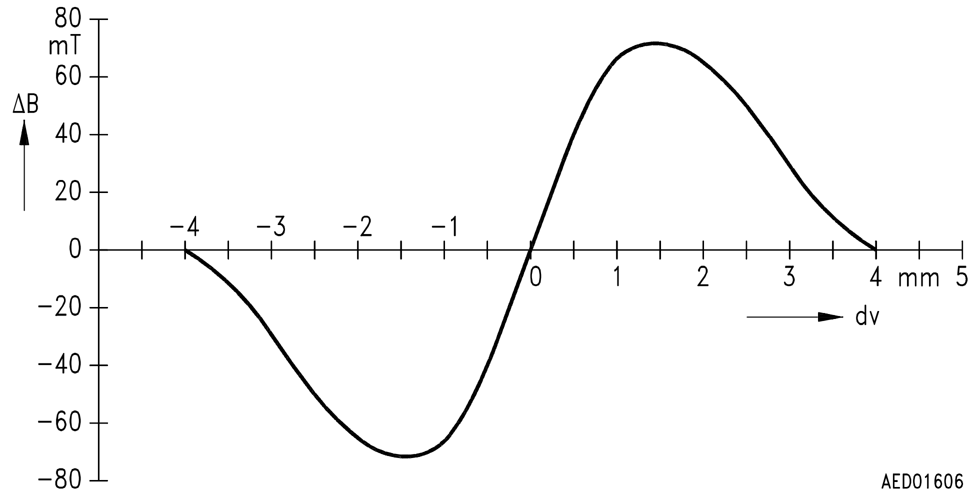


Figure 73
Differential Signal for a Pitch T = 8 mm

Figure 74 shows the influence of slanted teeth.

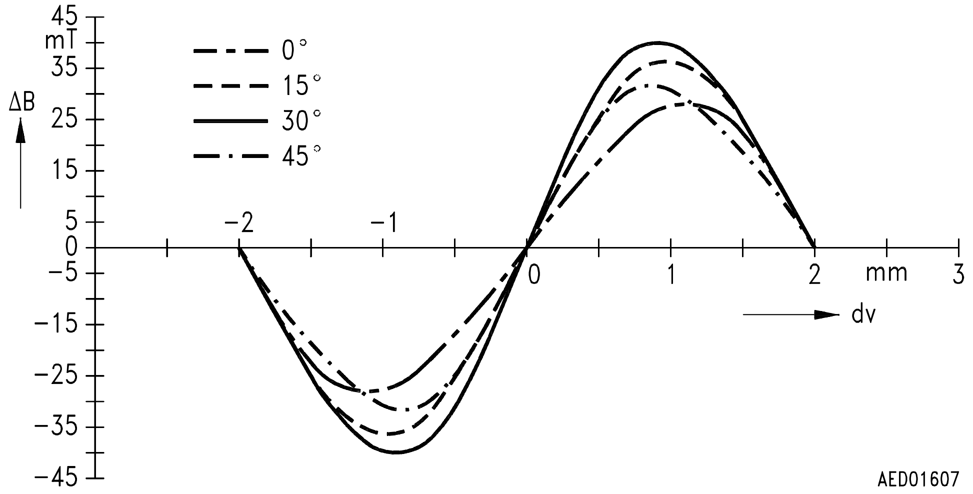


Figure 74
Differential Signal for Teeth with Different Slant

The differential signal for different tooth height Zh for T = 5 mm is shown in **Figure 75**. Zh equal to 5 mm already produces a large amplitude. A further increasing of Zh only leads to small improvements.

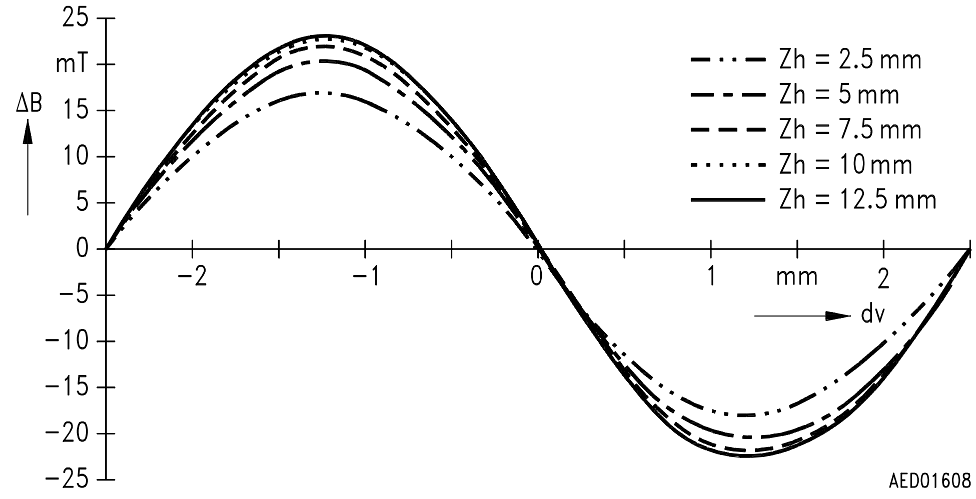


Figure 75
Differential Signal as a Function of Tooth Height, T = 5 mm

Of special interest, together with the influence of tooth geometry, is the signal behaviour of the sensor for varying airgaps dA. in **Figure 76** the differential signal of a toothed wheel with T = 4 mm and dv = 1 mm is shown as a function of the effective airgap.

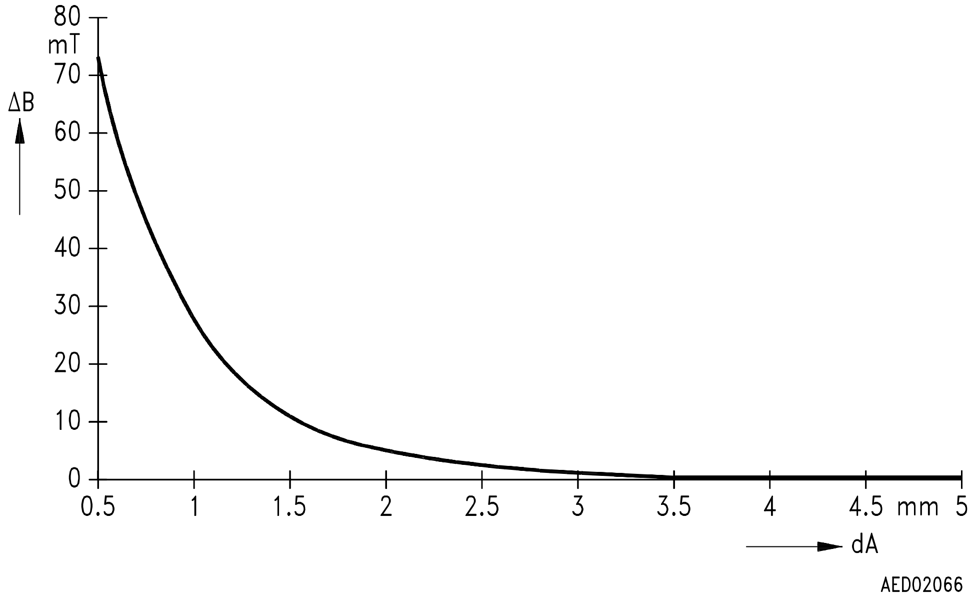


Figure 76
Differential Signal as a Function of Airgap dA for T = 4 mm and dv = 1 mm

A summary of the discussed points is shown in **Figure 77**:

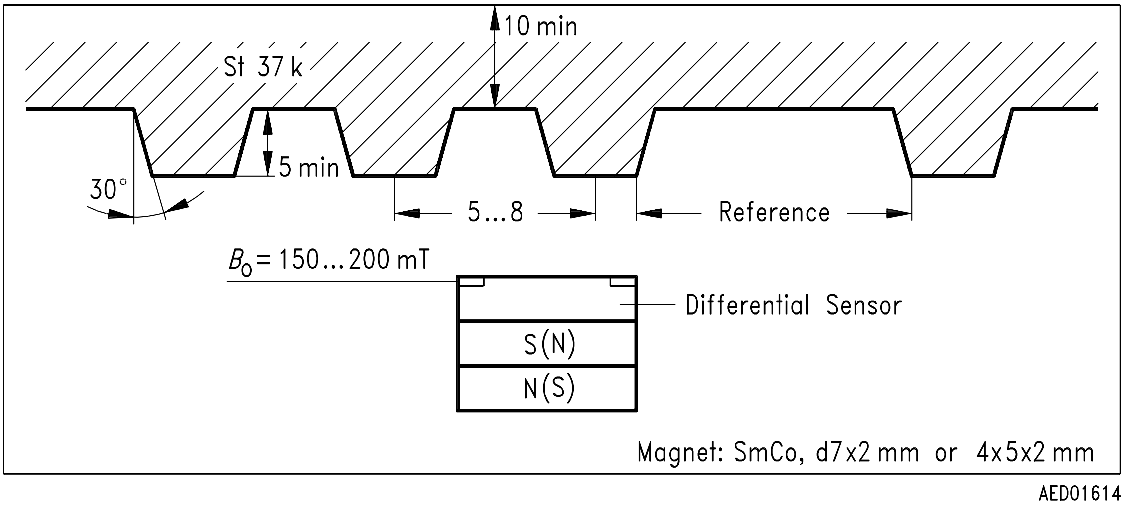


Figure 77
Optimum Application Configuration for the Differential Sensors, Dimensions in mm