Electrical Tests and Application Circuit

- The sockets or integrated circuits must not be conducting any voltage when individual devices or assembled circuit boards are inserted or withdrawn, unless works' specifications state otherwise. Ensure that the test devices and power supplies do not produce any voltage spikes, either when being turned on and off in normal operation or if the power fuse blows or other fuses respond.
- When supplying bipolar integrated circuits with current, the negative voltage (– V_S or GND) has first to be connected. In general, an interruption of this potential during operations is not permissible.
- Signal voltages may only be applied to the inputs of ICs when or better after the supply voltage is turned on. They must be disconnected when or better before the supply voltage is turned off.
- Power supplies of integrated circuits are to be blocked as near as possible at the supply terminals of the IC. With bipolar ICs it is recommended to use a low-inductance electrolytic capacitor or at least a paralleled ceramic capacitor of 100 nF to 470 nF for example. Using ICs with high output currents, the necessary value of the electrolytic capacitor must be adapted to the test or application circuit. Transient behaviour and dynamic output resistance of the power supplies, line inductances in the supply and load circuit and in particular inductive loads or motors have to be considered. When switching off line inductances of inductive loads, the stored power has to be consumed externally, unless otherwise specified (e.g. by an electrolytic capacitor, diodes, Z-diodes or the power supply). Also a switching off of the supply voltage prior to the load rejection should be taken into account.
- ICs with low-pass characteristic of the output stages (e.g. PNP drivers or PNP/NPN end stages), normally need an additional external compensation at the output. This applies particulary to complex loads. The output of AF power amplifiers is compensated by the Boucherot element. In individual cases, bridge circuits only need a capacitance for bypassing the load. Depending on the application it is, however, also recommended to connect one capacitor from each output to ground.
- Observe any notes and instructions in the respective data sheets.

7 Application Notes

7.1 Silicon Hall ICs

7.1.1 Magnetic Sensors

Measurement Configurations

Two separate methods for the detection of position or rotational motion using magnetic sensors can be distinguished. In the first case, the magnetic flux is varied by approaching or removing a magnet to/from the sensor or vice versa. This mechanism is suitable for position measurement or for non-contact switching. In rotational applications a rotating ring magnet or a ferromagnetic gear wheel modulate the flux through the sensor. This mechanism is applied when angular position or velocity has to be detected. In **Figure 7** the possible measurement configurations are shown in detail.

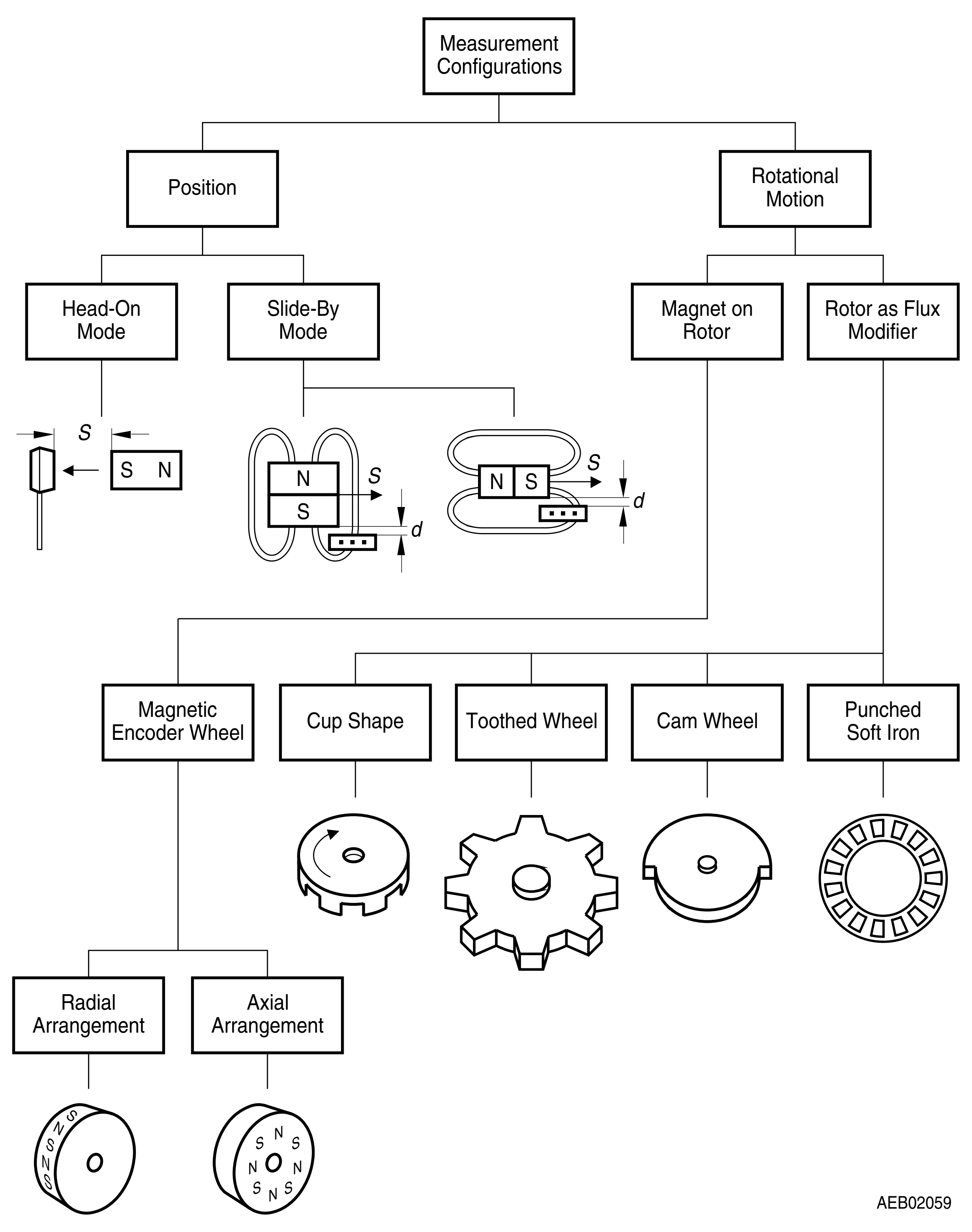


Figure 7
Measurement Configurations

Translational applications consist of two alternative functions, the Head-On Mode and the Slide-By Mode.

Head-On Mode

This is the simplest method with the magnet approaching from the front. Advantages of this mode are the simple mechanical design and the low sensitivity to lateral motion of the magnet. The flux density plot in **Figure 8** shows that the displacement characteristics are nonlinear, for position detection the switching points of the sensor therefore have to be very precise. Also, a zero flux state cannot be achieved. Additionally the head-on mode bears the risk of damage to the sensor when the measurement range is exceeded (direct physical contact with the magnet). Unipolar switches, i.e. the TLE4905L, are suitable for head-on mode operation.

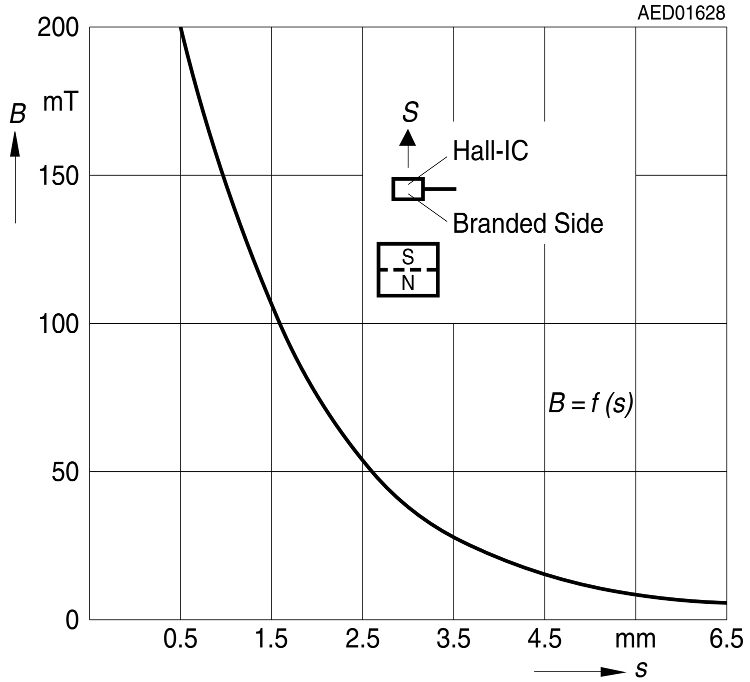


Figure 8
Magnetic Flux Density as a Function of the Distance *S* between Sensor and Magnet (Magnet: VX 145, Vacuumschmelze)

Slide-By Mode A

The magnet is led past the IC with one magnetic pole facing towards the chip surface. With this arrangement steep slopes and a zero or even negative fields are reached (in the case of a passing southpole). This allows for wider switching tolerances of the sensor. Sensor damgage due to overtravel of the magnet is excluded. This mode is, however, very sensitive to the lateral tolerances of the magnet, as the drastic variation of flux density versus air gap in **Figure 9** shows. As for the head-on mode, the slide-by mode A is suitable for unipolar switches, i.e. the TLE4905L.

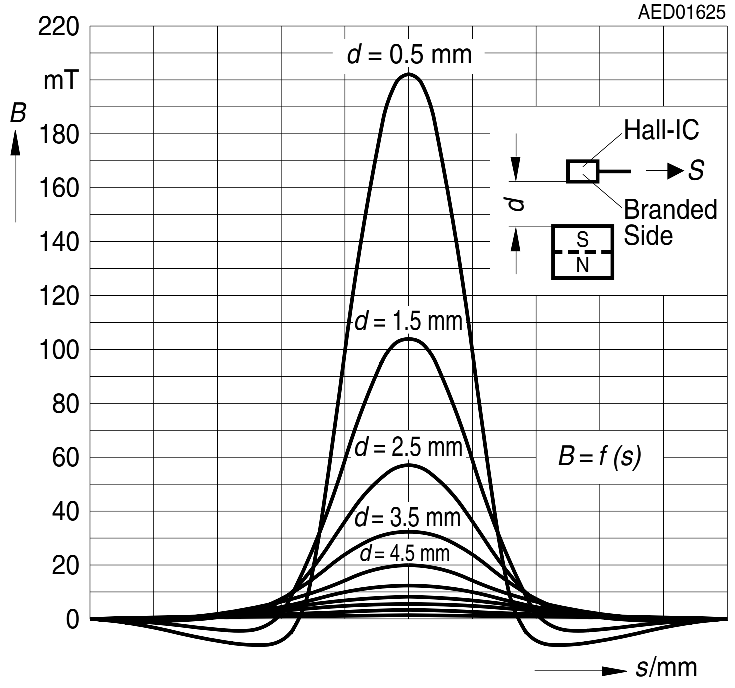


Figure 9
Magnetic Flux Density versus Displacement S in the Slide-by Mode A, Distance d as Parameter (Magnet: VX 145, Vacuumschmelze)

Slide-By Mode B

The magnet is led past the IC sidewards with both poles perpendicular to the chip surface, as shown in **Figure 10**.

Both magnetic poles are used in this application. With this arrangement the highest flux density swing, which is very important for operational reliability, is achieved. Bipolar switches with different hysteresis as well as unipolar switches, i.e. the complete TLE49x5 family, can operate in this mode.

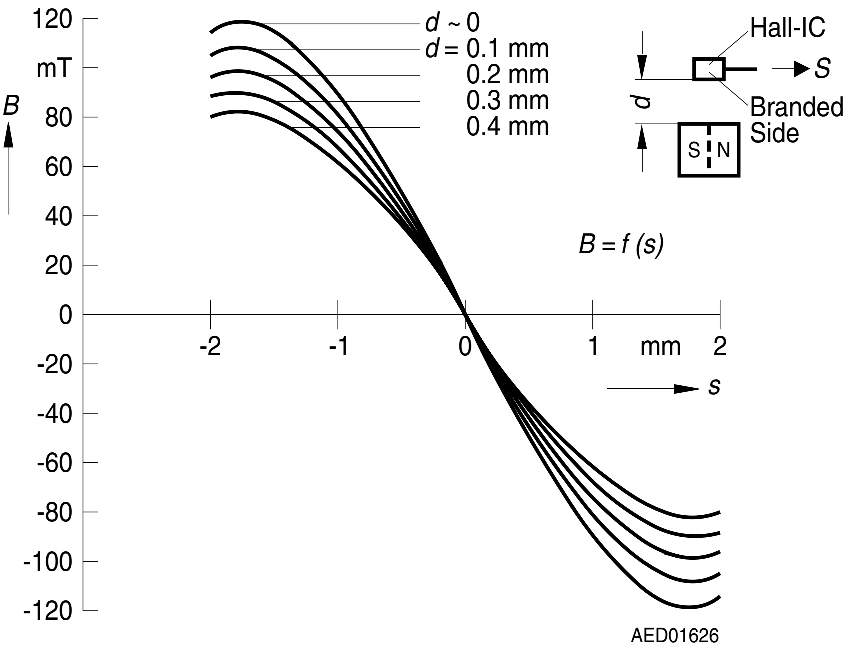


Figure 10
Magnetic Flux Density in the Slide-by Mode B, Distance *d* as Parameter (Magnet: VX 145, Vacuumschmelze)

Rotational applications serve to detect angular position, displacement or velocity. The first decision that must be made is whether the rotor is used as a generator for the magnetic field or as a modulator of the magnetic field strength.

Rotor as Magnetic Field Generator

A magnetic encoder wheel may be used in a radial or axial configuration, as in **Figure 7**.

Ferromagnetic Rotor as Flux Modulator

For high precision angular position and speed measurements, rotors that modify the flux through the sensors have several advantages over magnetic rotors. When operating a sensor with a ferromagnetic rotor, a constant magnetic field must be provided by a back biasing permanent magnet attached to the rear side of the sensor. The turning rotor modulates the magnetic field, i.e. a ferromagnetic material in front of the sensor acts as a concentrator and increases the flux density of the magnet through the sensor.

Axial mounting of the sensor requires toothed wheels, whereas radial mounting is performed with vanes or punched soft iron rings. The application with a toothed wheel has the advantage that already existing wheels can be used. Especially for high precision toothed wheel applications, differential sensors based on two Hall cells give best results together with the lowest assembly requirements

Vane applications are very sensitive to radial bearing play, there is, however, only little sensitivity to axial play. Toothed wheels are used in automotive industry for ignition systems. ACPS systems (Active Crankshaft Position Sensing) that require a very precise angular position readout are based on a toothed crankshaft wheel in combination with a differential sensor. Also for speed sensing in gearbox applications, toothed wheels are the obvious solution.

For AWSS systems (Active Wheel Speed Sensing) the rotor wheel can be directly molded into the bearing, requiring therefore a flat punched soft iron wheel. Since the flux density change of a molded punched iron is very small (in the range of a few mT), the sensor must be able to switch very small field changes. Also for this application, differential sensors yield optimum results.

7.1.2 Magnet Choice

The described Hall IC applications always use one or more permanent magnets. Either the magnet itself moves, or its magnetic field is modulated by a ferromagnetic part. For the right choice of the magnet for a specific application, several factors must be taken into consideration.

Mechanical Factors

- Dimensions and tolerances
- Thermal expansion coefficients
- Is there a shaft hole required for the rotating part and what is its maximum eccentricity

Magnetic Factors

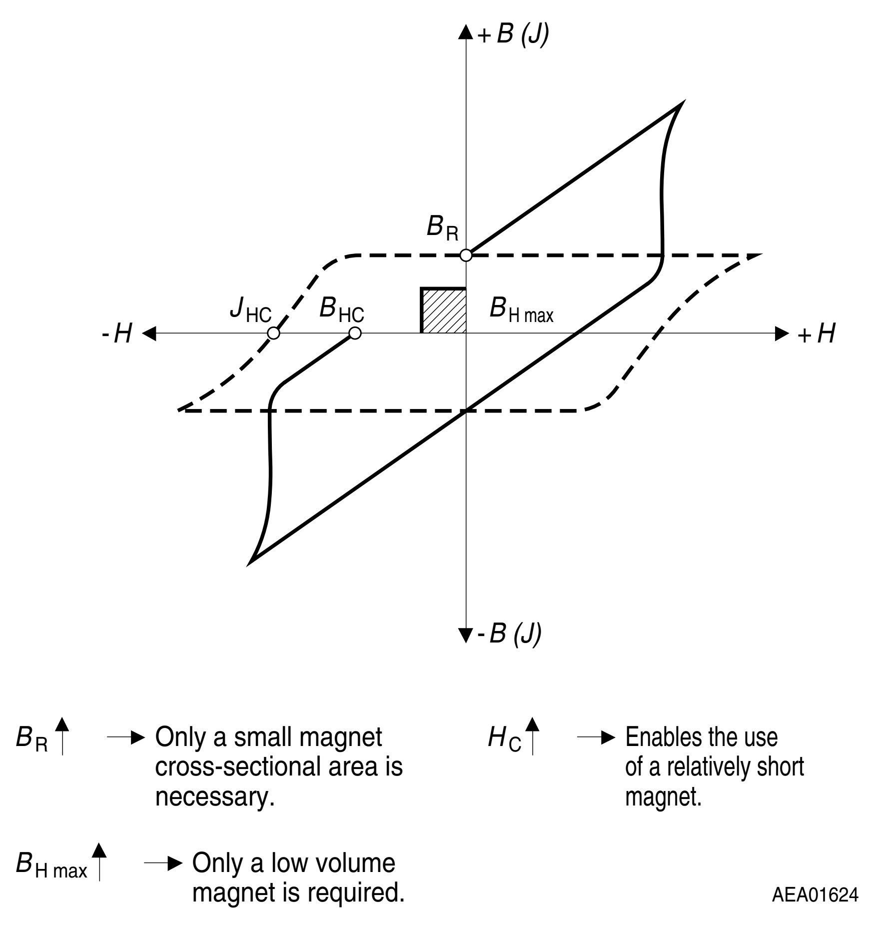
- Quantity, alignment and fitting accuracy of the magnetic poles
- Flux density at the specified airgap
- Magnetic temperature coefficient

Environmental Factors

– Resistance of the materials to the environment with regard to temperature, chemical composition and electrical potential

Of special importance are the characteristics and properties of the different permanent magnet materials. The three most important characteristics are the remanence B_R, the coercive force H_C and the density product $B_{H\,max}$:

- The remanence B_R [Tesla or Gauss] is a measure of how high the remaining magentic flux is after full magnetization in a closed circuit.
- The coercive force H_C is the field strength which must be applied in order to bring the flux density B or the magentization J back to zero (${}_BH_C$, ${}_JH_C$).
- The absolute maximum energy product $B_{H\,max}$ [kJ/m^3] is of great significance for the performance of the permanent magnet. It is calculated from the B-H values obtained during the demagnetization of a permanent magnet, see **Figure 11**.



$B_R\uparrow$ → Only a small magnet cross-sectional area is necessary.

$H_C\uparrow$ → Enables the use of a relatively short magnet.

$B_{H\,max}\uparrow$ → Only a low volume magnet is required.

Figure 11
Magnetic Hysteresis Loops

In the following some common permanent magnets and their properties are discussed.

Rare-Earth Cobalt Sinter Material

This material is an alloy of a rare-earth material and Cobalt. Rare-earth materials are for example Samarium or Selen with the corresponding magnet materials Sm_2CO_{17} and $SeCO_5$, respectively. Rare-earth Cobalt magnets have the highest performances of all magnet types, however they are also the most expensive ones. They allow for high temperature ranges, up to about 250 °C for Selen Cobalt and up to 300 °C for Samaraium Cobalt. Also their maximum energy product is by far higher than the ones of other magnets. The long term stability of rare-earth based magnets is very good. Due to the hardness and brittleness, these materials cannot be shaped other than by grinding.

AlNiCo Alloys

As the name implies, AlNiCo magnets are alloys containing Aluminium, Nickel, Cobalt, Iron and additives which are offered in a wide range of properties. Among all magnets, AlNiCo magnets have the best thermal properties, i.e. the lowest temperature coefficient of expansion. The material is easily formed, it can be cast or sintered to any shape from metal powders.

Also the mechanical stability is good. This, and the above properties, make AlNiCo a suitable magnet material for mass production. However, the coercive force of AlNiCo is low and its longterm stability is rather moderate. AlNiCo is too hard and brittle to be shaped.

Sintered Compund Material from Neodymium, Iron and Boron (NdFeB)

As the name says, an alloy of Neodymium, Iron and Boron. This material has a high maximum energy value and a very high field strength. The drawbacks are the low temperature range and the susceptibility to corrosion. Also the relatively high reversible temperature coefficient of remanence must be mentioned.

Barium and Strontium Ferrites

These types belong to the group of ceramic magnets. The ferrites, typically Barium or Strontium, and the base ceramic material are compacted and sintered. A high coercive force and a low price are characteristic for ceramic magnets. As disadvantages the low remanence and the very high reversible temperature coefficient can be mentioned.

7.1.3 Uni- and Bipolar Hall IC Switches (TLE49x5)

Applications

- Detection of rotational speed
- Detection of linear position and rotational position
- Non contact limit switch
- Flow-rate measurement
- Brushless commutation

Main Features

- For uni- and bipolar fields
- Clean, rapid and bounce-free switching
- No mechanical wear
- Low power consumption
- Insensitive to contamination
- Wide temperature range
- Reverse polarity protection

General Description

The integrated Uni- and Bipolar Hall IC switch series TLE49x5 is designed specifically for industrial, automotive and consumer applications. These magnetic sensors with digital output are available as unipolar and bipolar switches and bipolar latches.

The bipolar circuit includes the Hall element, an operational transconduction amplifier and a Schmitt-Trigger. Compensation electronics guarantees a linear temperature behaviour of the switching thresholds with a negative slope. A quadruple Hall cell arrangement minimizes the piezoresistive effect (sensitivity to mechanical stresses). The open-collector output can sink up to 100 mA.

Design and Function of the Chip

A magnetic field acting perpendiculary to the chip surface generates a voltage on the probe terminals of the Hall element. This voltage is amplified and fed into a Schmitt-Trigger that drives an npn-transistor, the collector of which gives the output. If the induction exceeds the turn-on induction, the output transistor will conduct. If the magnetic field is reduced by the hysteresis, the output ceases to conduct.

To minimize the variation of the switching points as a result of supply voltage drift and ambient temperature, the Hall probe is fed from a stabilized voltage source. The switching thresholds are stabilized in the operating temperature range by a compensation circuit.

The devices are protected internally against reverse polarity protection.

The TLE4905L is a unipolar switch, i.e. it only reacts to a magnetic south pole. Hereafter the flux caused by a magnetic south (north) pole is defined as a positive (negative) flux. If an applied positive magnetic flux density exceeds the turn-on value B_{OP}, the output conducts. If the magnetic flux density falls below the positive turn-off value B_{RP}, the output is inhibited again. The typical application is that of a position switch actuated by the proximity of a permanent magnet.

The TLE4935/35-2/45 are bipolar switches. They switch into a conducting state when the positive flux density B_{OP} is exceeded and they do not switch back to the inhibited state until the equally strong negative flux density B_{RP} is applied. In the absence of a field the output retains in the last state (latch). Bipolar switches are applied for electronic commutation of brushless DC motors, position detection and speed measurement of a rotating magnetic bar or magnetic encoder wheel.

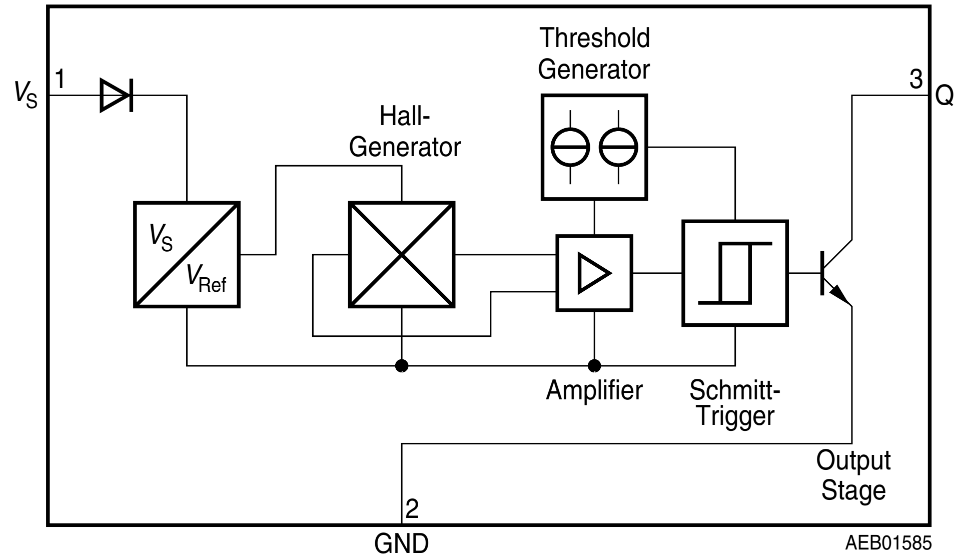


Figure 12
Block Diagram of Uni- and Bipolar Hall IC Switches

The following sections present the test results of the DIN 40839-1 and -4 tests and show how the Hall IC switches are to be used in equipment guaranteeing Electromagnetic Compatibility.

Injection of Supply Line Transients (DIN 40839-1)

Internally the devices TLE4905/35/35-2/45/45-2 have no protection against surge voltages, only against reversal of the supply voltage, **so the supply voltage limit 40 V $<$ V_s $\leq$ 32 V must not be exceeded under any circumstances**.

Stage 1: Without External Protection

If the devices are operated in the application circuit according to the data sheet, the high pulse amplitudes (with the exception of pulses 1 and 4) exceed the limit of the supply voltage. Without a protection circuit there will naturally be failures.

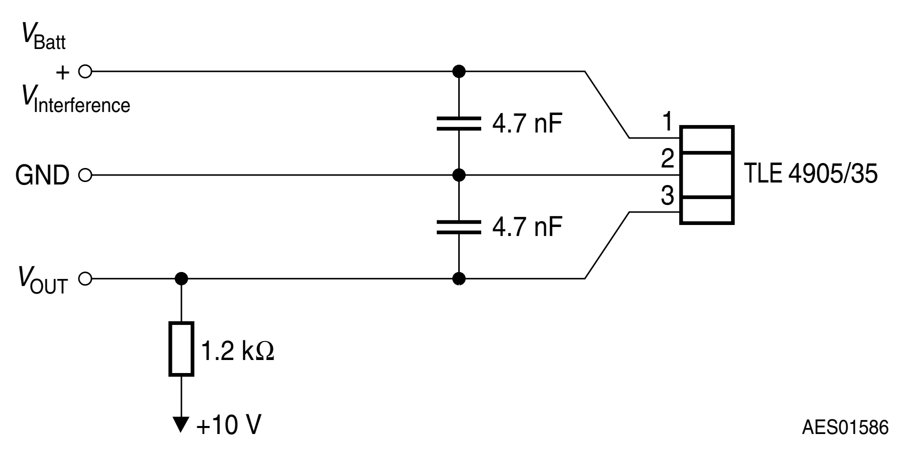
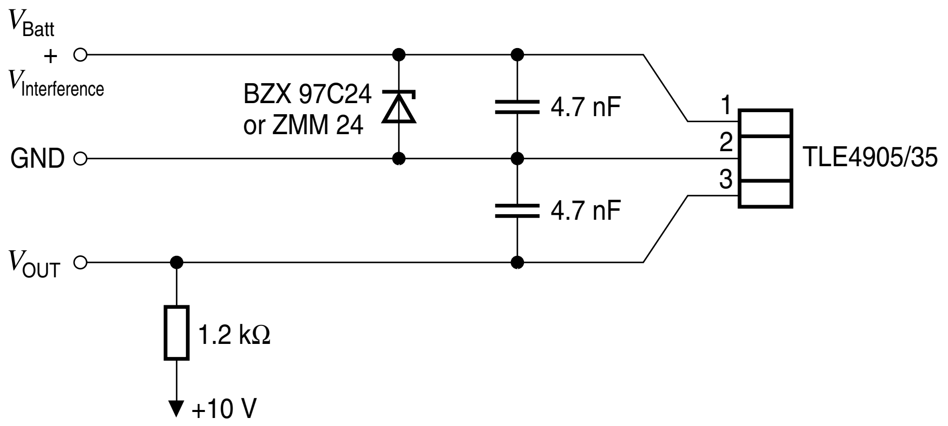


Figure 13
TLE4905/35/35-2/45/45-2 without External Protection

Stage 2: Simple Surge Protection

In this case a simple zener diode (or also a suppressor diode) is used for surge protection.



Functional States

Test Pulse	Severity Level	
	I	II/III/IV
1	C	-E-
2	A	-E-
3a	C	-C-
3b	A	-A-
4	C	-C-
5	E	-E-

A: Normal function

C: No function during interference, otherwise normal

E: Total failure

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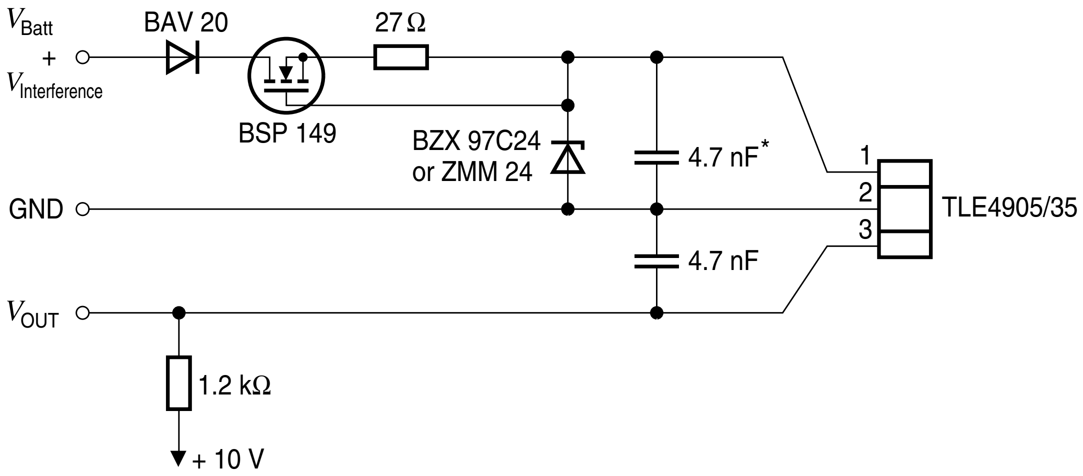
Figure 14
TLE4905/35/35-2/45/45-2 with Simple Surge Protection

Stage 3: Complete Protection

The illustrated protective circuitry is effective against all standard interference pulses of severity level IV. The lower limit of the supply voltage for the circuit is slightly higher (approx. 1 V) than that of the devices.



Functional States

Test Pulse	Severity Level
	I/II/III/IV
1	-C- A*)
2	-A-
3a	-C- A*)
3b	-A-
4	-C-
5	-A-

A: Normal function

C: No function during interference, otherwise normal

*) With 4.7 µF Tantal-Elko function during pulse possible

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Figure 15
TLE4905/35/35-2/45/45-2 with Complete Protective Circuitry

Radiated Interference (DIN 40839-4)

The device in the application circuit according to **Figure 13** is exposed to an electromagnetic field in the range from 100 kHz to 750 kHz with field strength of

100 V/m with 1 kHz AM
200 V/m without AM

in a TEM cell. The tested item is located at the end of a 20 cm long, open adapter board in the center of the cell.

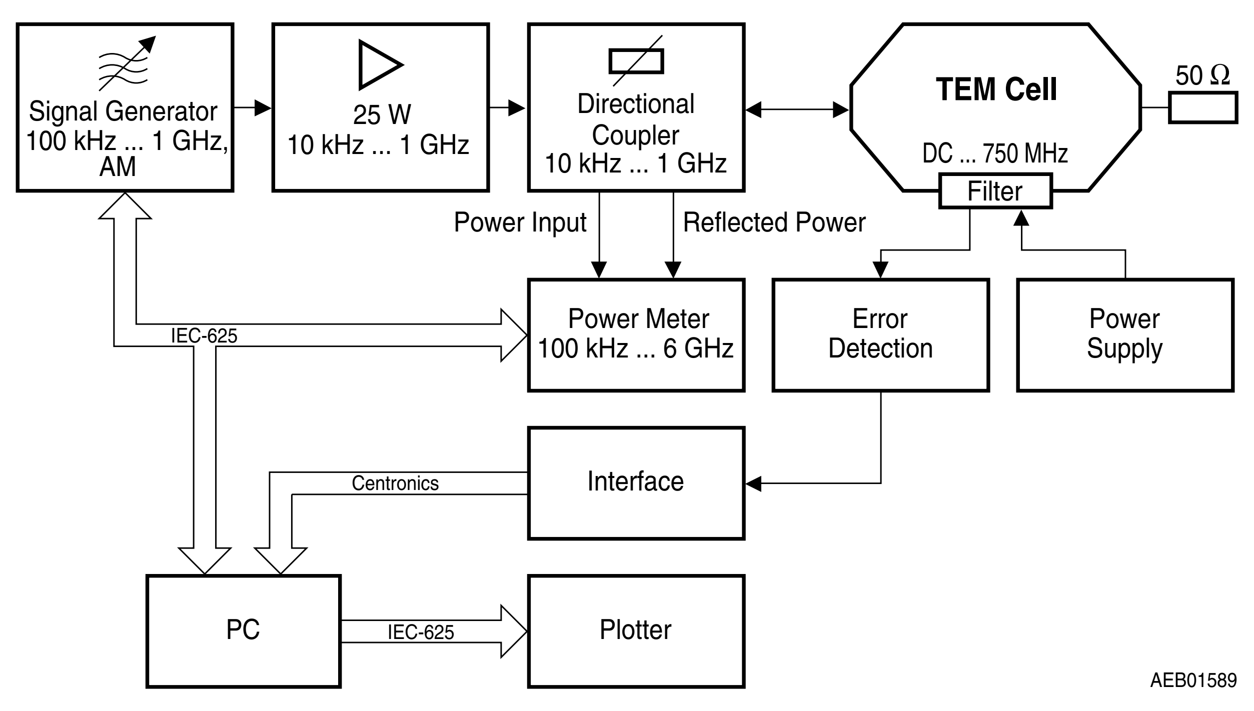


Figure 16
Test Setup with TEM Cell

No switching error occurs, the previously set Low or High states are maintained. The same applies for the minimum operating voltage.

7.1.4 Differential Hall IC TLE4921-5U

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 TLE4921-5U 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 TLE4921-5U 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.

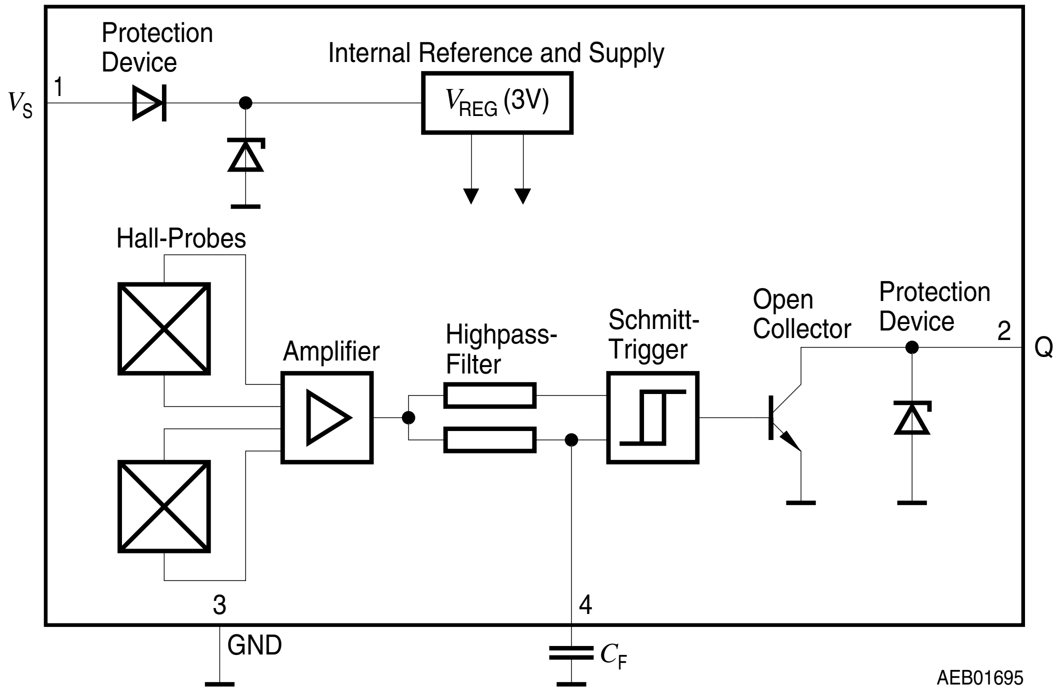


Figure 17
Block Diagram TLE4921-5U

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.

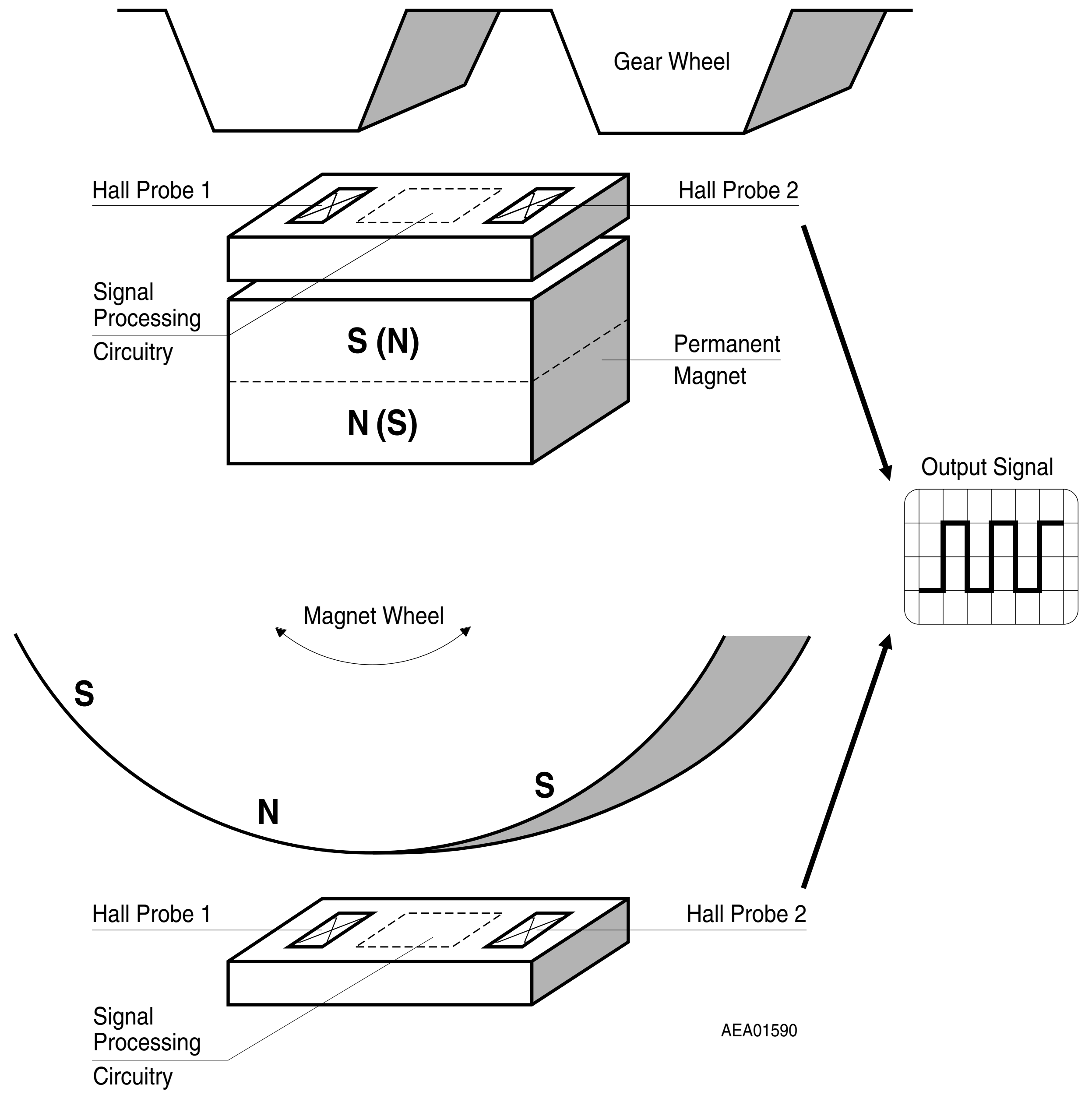
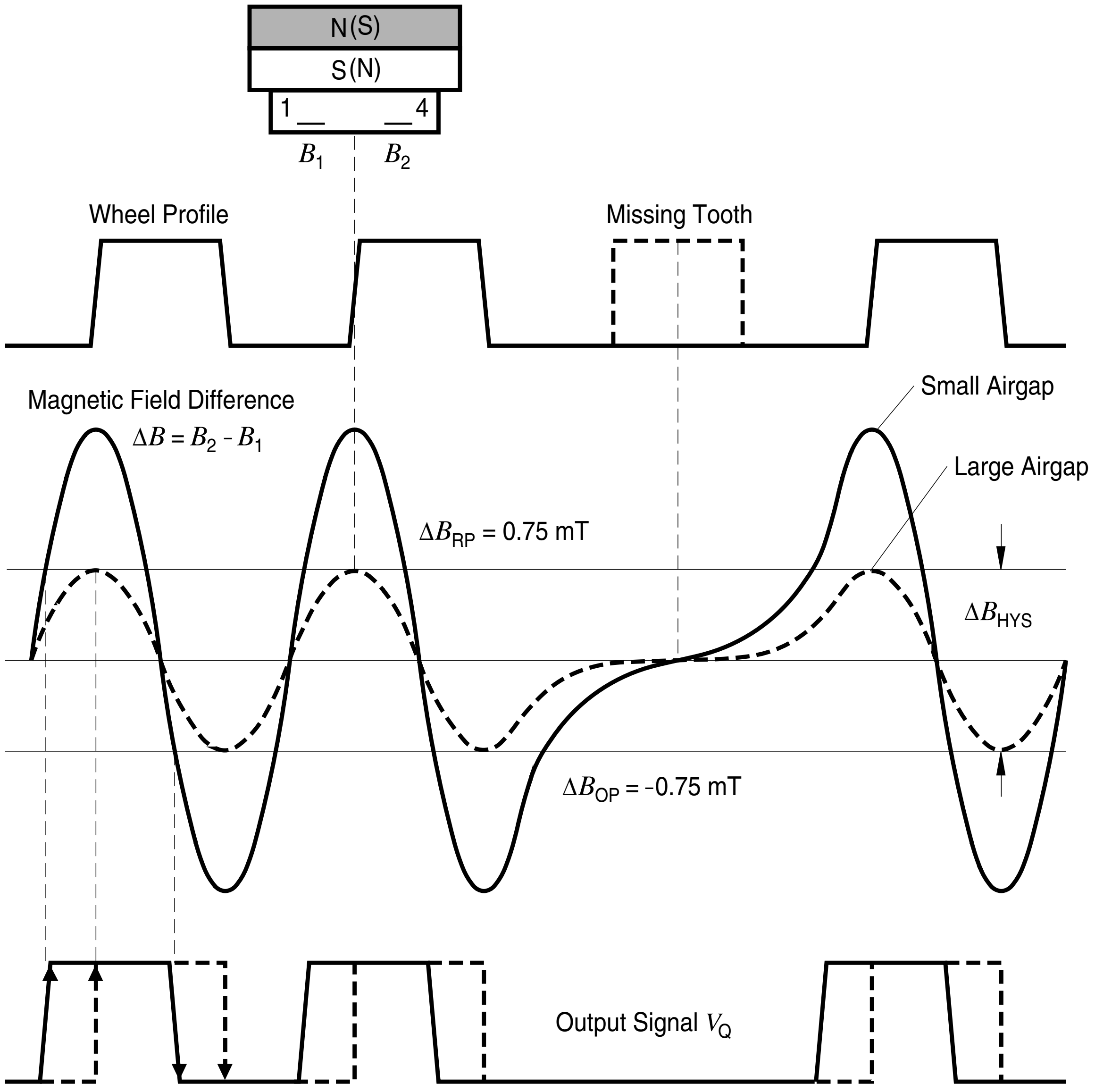


Figure 18
Application as a Gear Wheel Sensor and as an Encoder Wheel Sensor

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 TLE4921-5U 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 18**. 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: $B_2 - B_1 < \Delta B_{OP}$ switches the output ON (V_Q = LOW)
Release point: $B_2 - B_1 > \Delta B_{RP}$ 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 19
Sensor Signals Produced by a Toothed Gear Wheel

Gear Wheel, Sensing Distance and Angular Accuracy

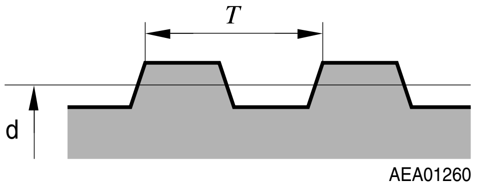
A gear wheel is characterized by its modulus:

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

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 × π/p
T	pitch $T = \pi \times m$ (mm)		

Figure 20
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 2

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

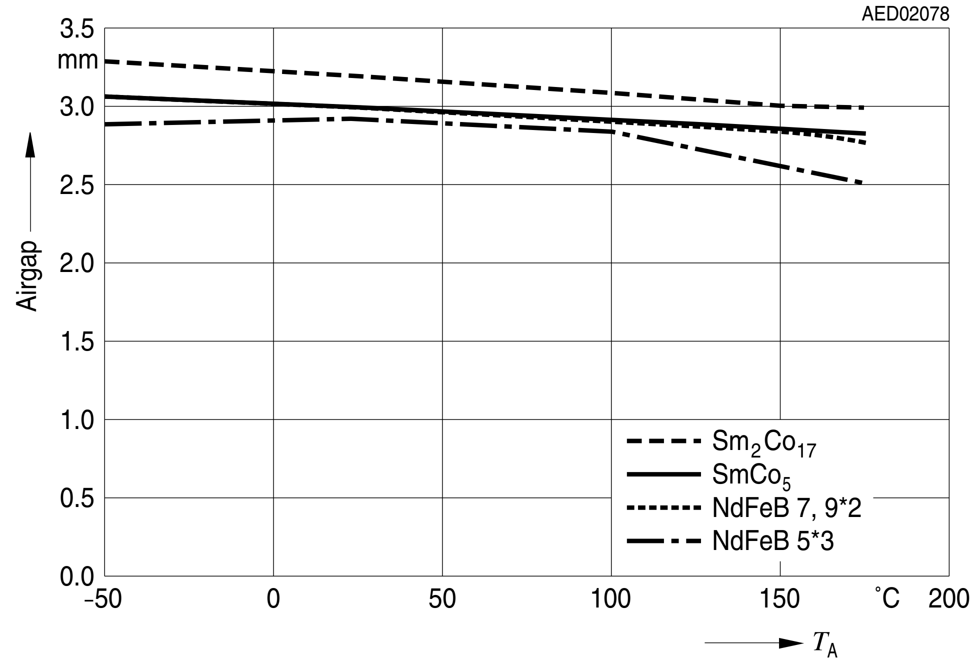


Figure 21
Maximum Sensing Distance for a Gear Wheel with Modulus 1,5 as a Function of Biasing Magnet

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

$$\Delta B_m = \frac{I_L \times R_C(T)}{S_C(T)} \qquad [4]$$

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: Radiated Interference (DIN 40839-4)

This test is carried out in a TEM cell. The setup is described in **Chapter 7.1.7** (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 22**. It is seen that over the whole frequency range the TLE4921-5U performs without disturbance up to the maximum field of 160 V/m. More details on the TEM measurements are available on request.

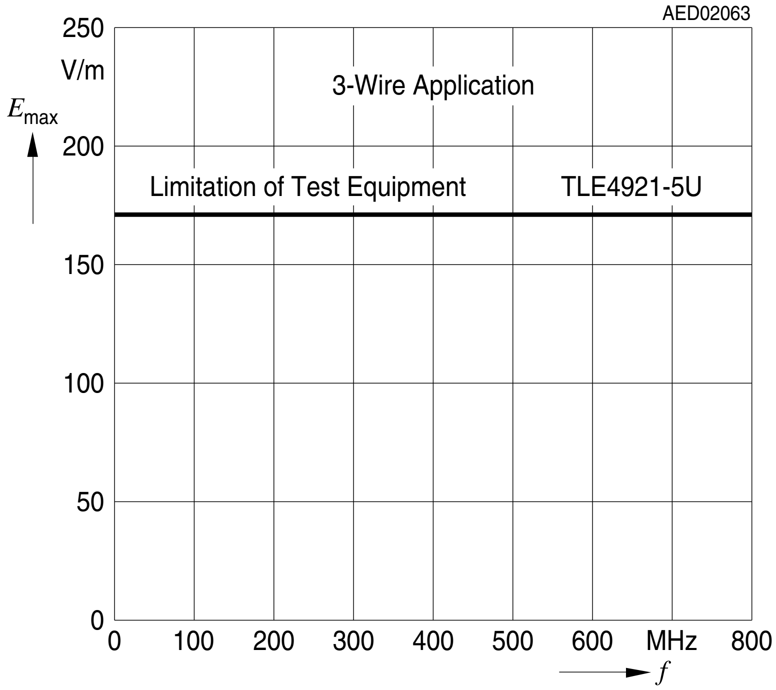


Figure 22
Results of the Radiated Interference Test with the TLE4921-5U

Optimization of TLE4921-5U 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 TLE4921-5U. The following recommendation is the result of EMI measurements carried out on the device during in-house testing.

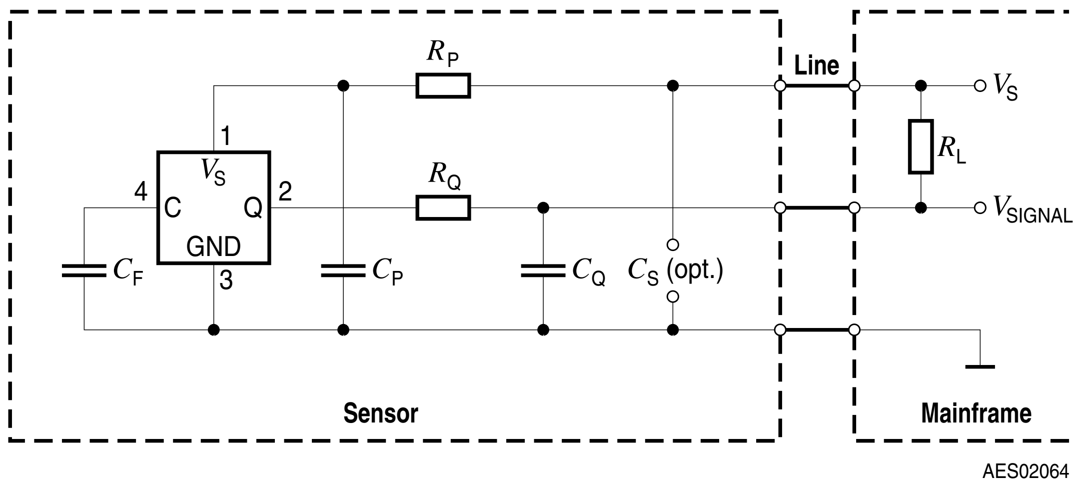


Figure 23
Optimized TLE4921-5U PCB Circuit for Three-wire Operation

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	Serves with C_q to smoothen the falling edge of V_{SIGNAL}, i.e. reduction of irradiated interference
C_q = 4.7 nF	
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 TLE4921-5U 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.

$$V_{\text{analog}} = \underset{\substack{\uparrow\\ \text{Operating voltage}}}{V_{\text{op}}} \times \underset{\substack{\uparrow\\ \text{Set monoflop time}}}{\text{RC}} \times \underset{\substack{\uparrow\\ \text{No. of teeth on wheel}}}{\text{T}}/60 \times \underset{\substack{\uparrow\\ \text{Revolutions per minute}}}{\text{rpm}}$$

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.

$$\text{Speed[rpm]} = \frac{\text{Counted pulses}}{T_{\text{window}}} \qquad \text{with } T_{\text{window}}[\text{s}] = \frac{60}{\text{Number of teeth}} \tag*{[5]}$$

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 24**.

A proven application circuit for analog sensing of rotational speed and sense is shown in **Figure 25**.

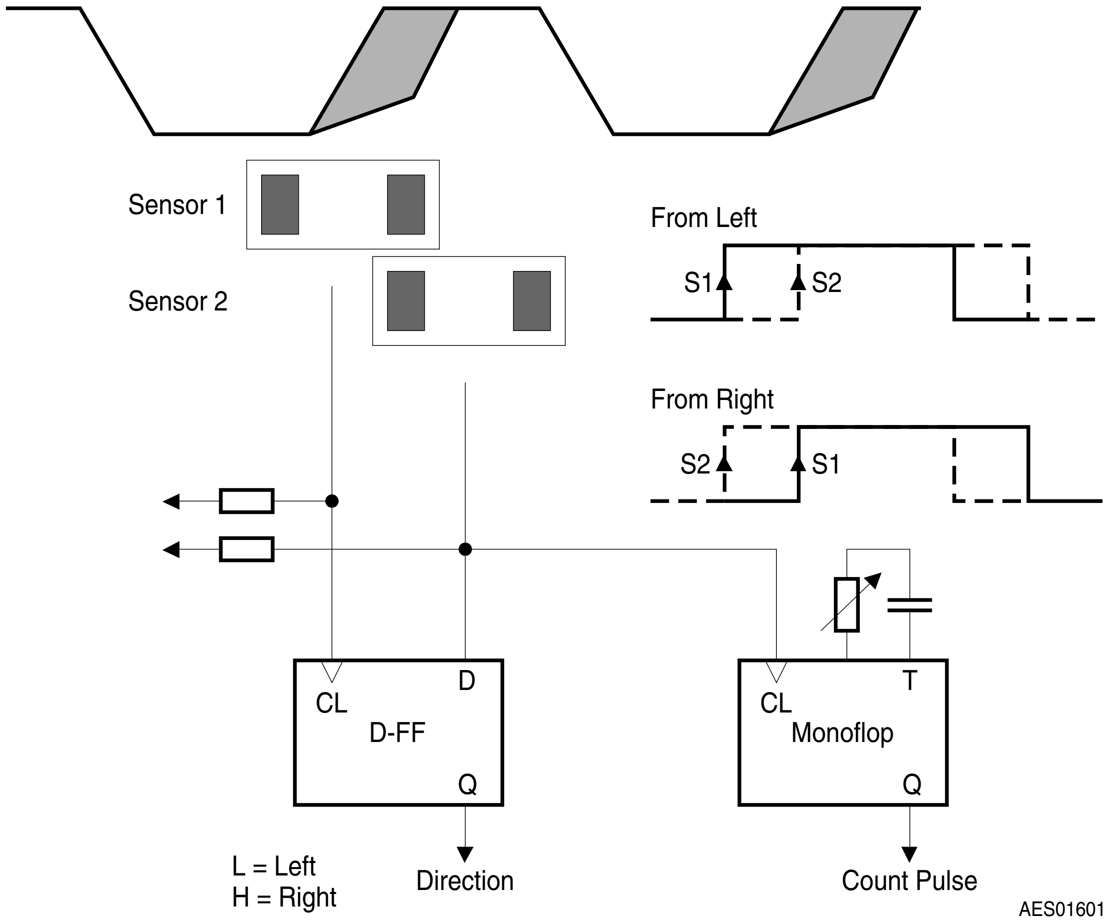


Figure 24
Detecting Sense of Rotation with Two Gear-Wheel Sensors

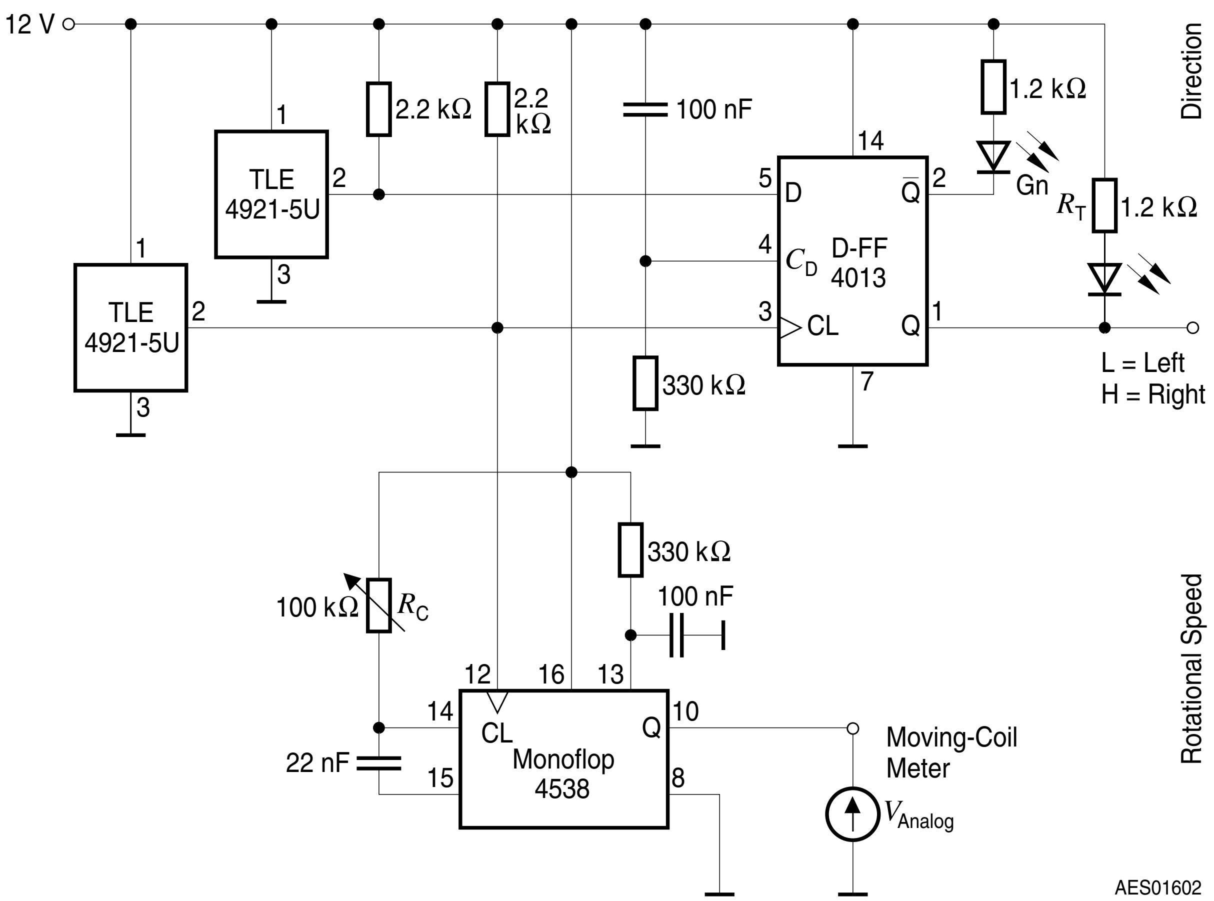


Figure 25
Application Circuit Rotational Speed/Rotational Sense

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 26**).

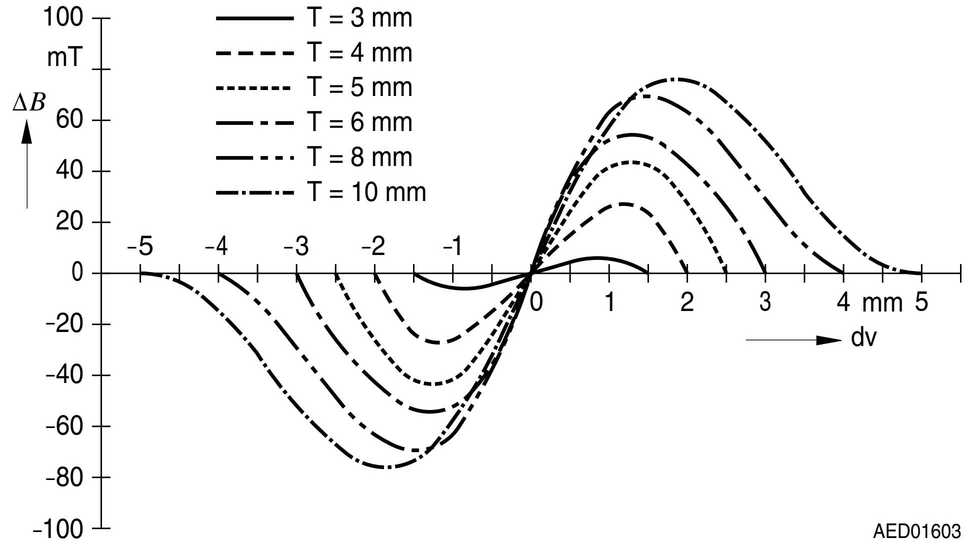


Figure 26
Differential Signal as a Function of Pitch T

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 27**).

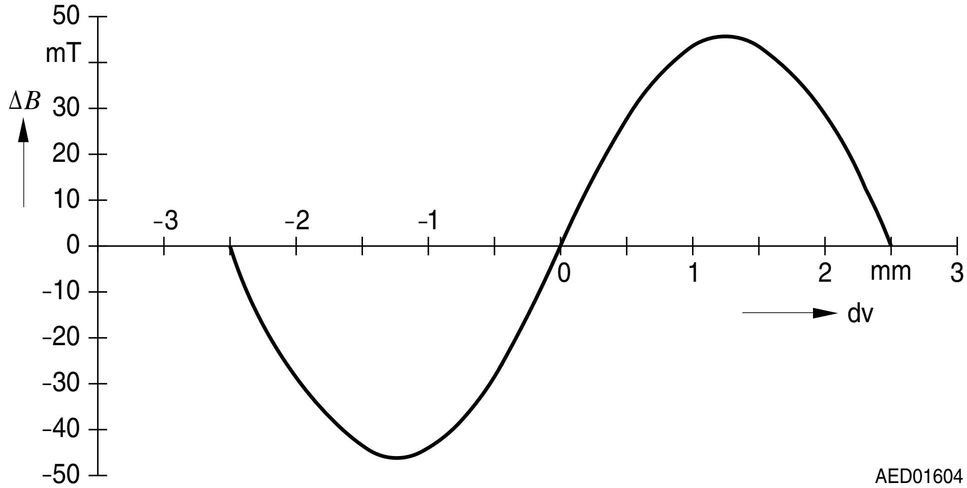


Figure 27
Differential Signal for a Pitch T = 5 mm

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 28**).

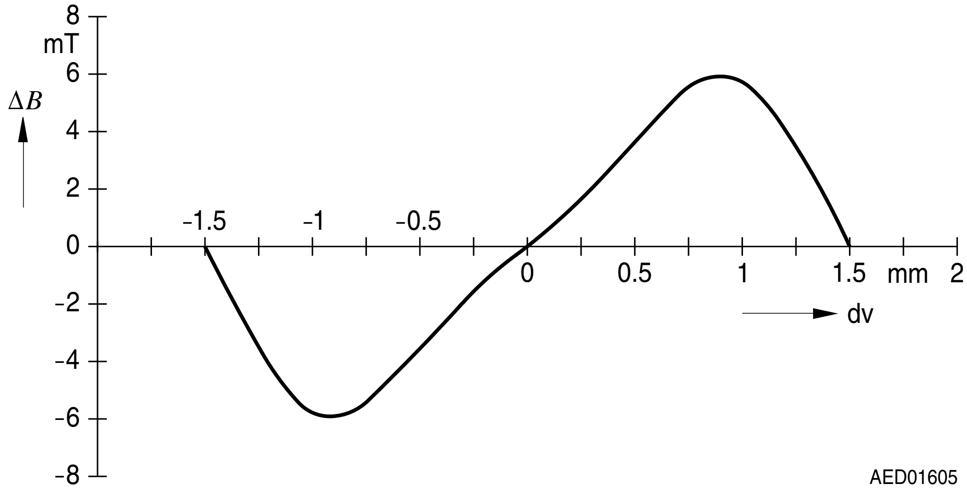


Figure 28
Differential Signal for a Pitch T = 3 mm

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 29**).

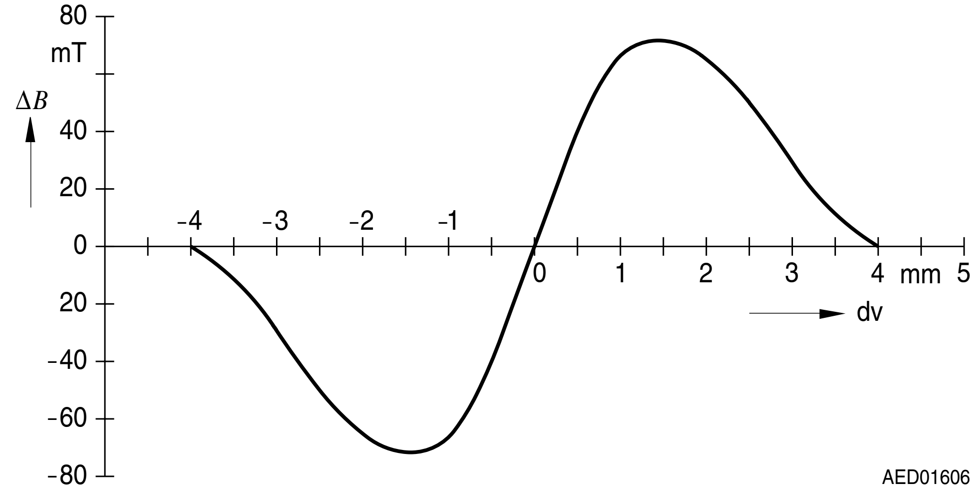


Figure 29
Differential Signal for a Pitch T = 8 mm

Figure 30 shows the influence of slanted teeth.

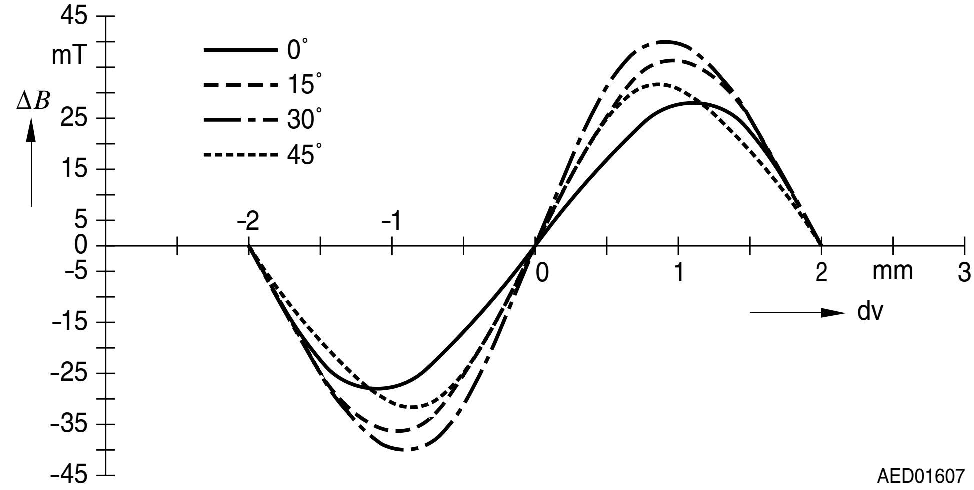


Figure 30
Differential Signal for Teeth with Different Slant

The differential signal for different tooth height Zh for T = 5 mm is shown in **Figure 31**. Zh equal to 5 mm already produces a large amplitude. A further increasing of Zh only leads to small improvements.

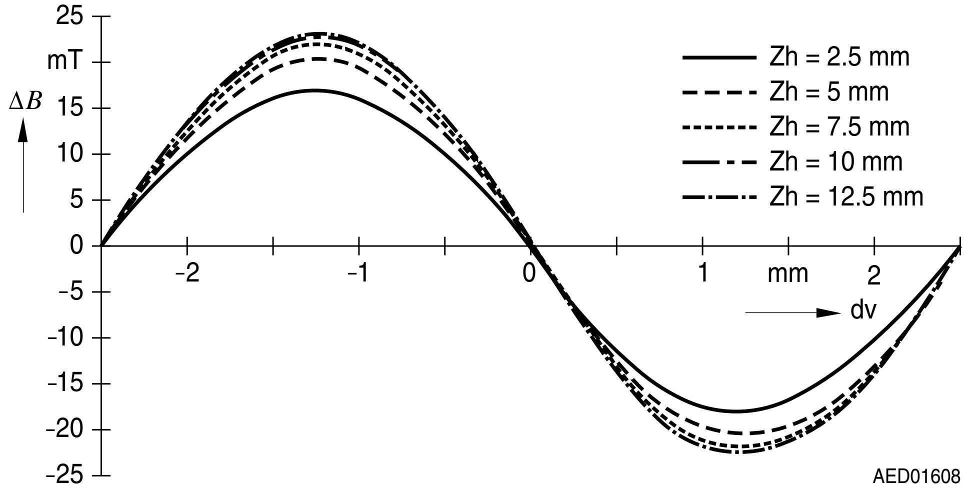


Figure 31
Differential Signal as a Function of Tooth Height, T = 5 mm

Of special interest, together with the influence of tooth geometry, is the signal behaviour of the sensor for varying airgaps dA. in **Figure 32** the differential signal of a toothed wheel with T = 4 mm and dv = 1 mm is shown as a function of the effective airgap.

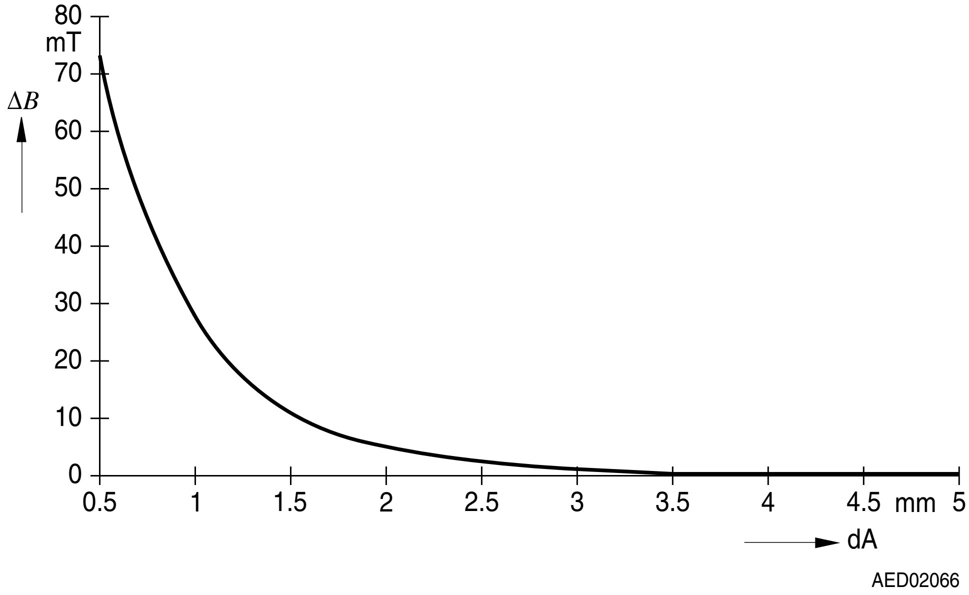


Figure 32
Differential Signal as a Function of Airgap dA for T = 4 mm and dv = 1 mm

A summary of the discussed points is shown in **Figure 33**:

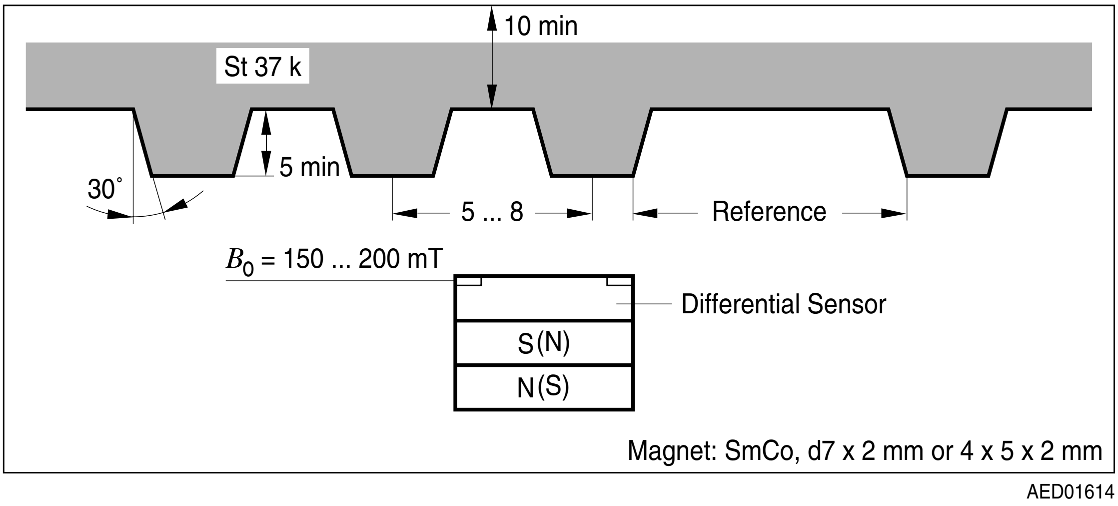


Figure 33
Optimum Application Configuration for the Differential Sensors, Dimensions in mm

7.1.5 Differential Hall IC TLE4923

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
- Reverse polarity protection
- Guarded against RF interference
- Wide temperature range
- Current interface

General Description

The TLE4923 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 TLE4923 is offered in an ultraflat package with three leads (P-SSO-3-6).

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.

The TLE4923 incorporates a current interface that enables transmission of the output signal through the supply current. Protection against reverse polarity as well as against EMI are integrated and allow application in the hostile environments found in the automotive industry.

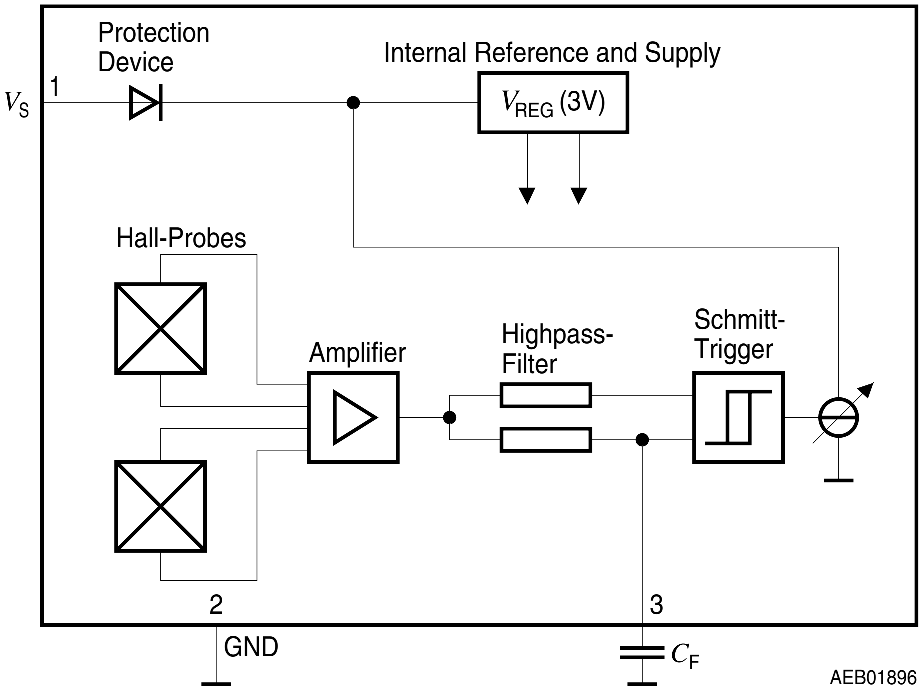


Figure 34
Block Diagram TLE4923

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.

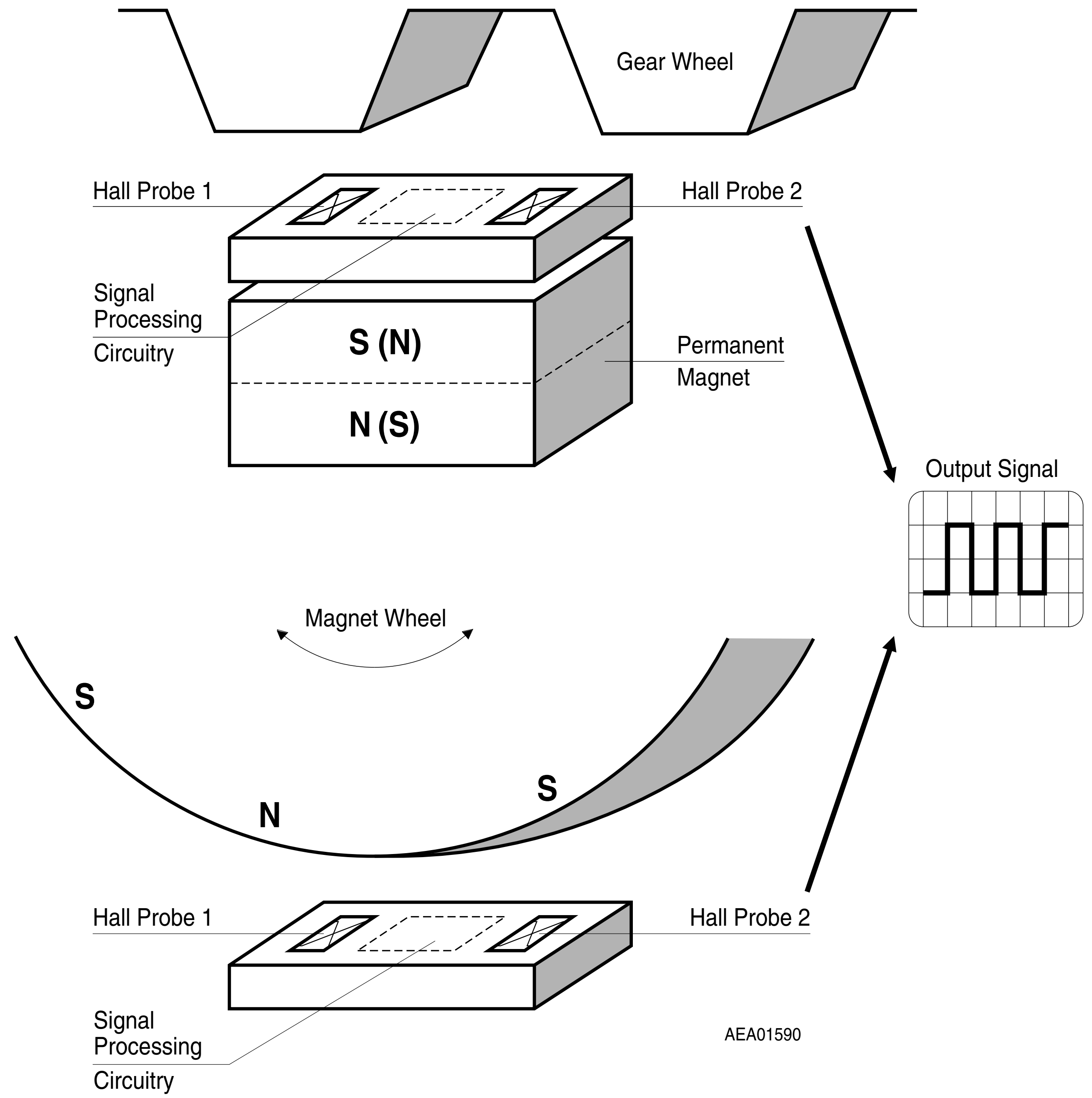
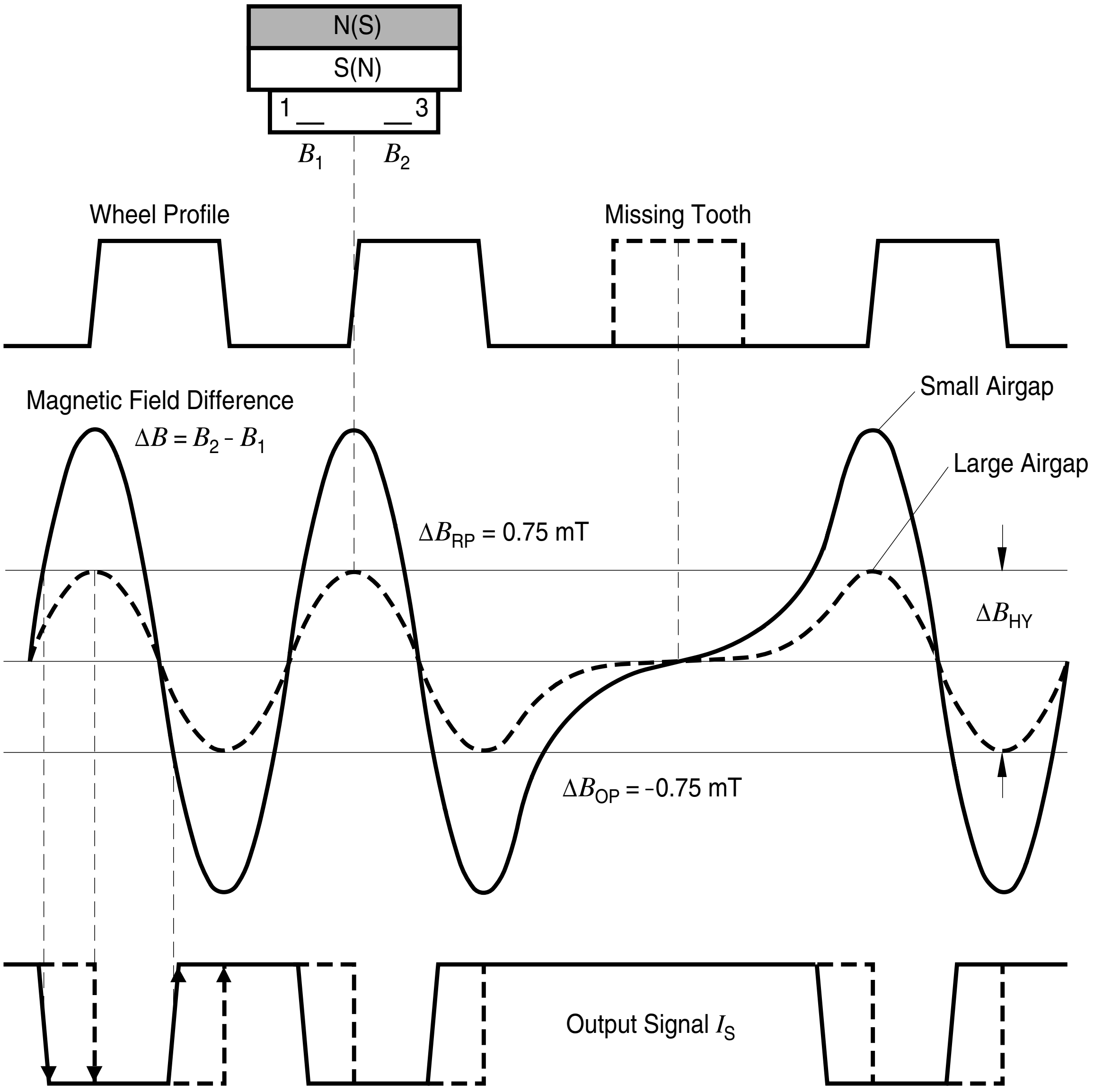


Figure 35
Application as a Gear Wheel Sensor and as an Encoder Wheel Sensor

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 current turns low (“OFF” state). This is the case when the tooth is sensed by the Hall probe 2 near pin 3 in **Figure 38.** As the difference falls below the lower threshold ΔB_{OP}, the ourput current turns high(“ON” state). This is the case when the Hall probe 1 near pin 1 sense 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).



$$\begin{array}{l} \text{Operate point: } B_2 - B_1 < \Delta B_{OP} \text{ switches the output ON} \\ \text{Release point: } B_2 - B_1 > \Delta B_{RP} \text{ switches the output OFF} \end{array} \left(\begin{array}{l} \text{high} \\ \text{low} \end{array} \text{current}\right)$$

$\Delta B_{RP} = \Delta B_{OP} + \Delta B_{HY}$

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

AED01900

Figure 36
Sensor Signals Produced by a Toothed Gear Wheel, Example TLE4923

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

$$\Delta B_m = \frac{I_L \times R_C(T)}{S_C(T)} \tag{6}$$

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)

For the measurements with the TLE4923 the test circuit as in **Figure 37** is used. The filter capacitor C_F = 470 nF is connected directly to pin 3, additionally a shunt capacitor C_S = 4.7 nF is connected in the supply line. A load resistance R_S = 180 Ω is used.

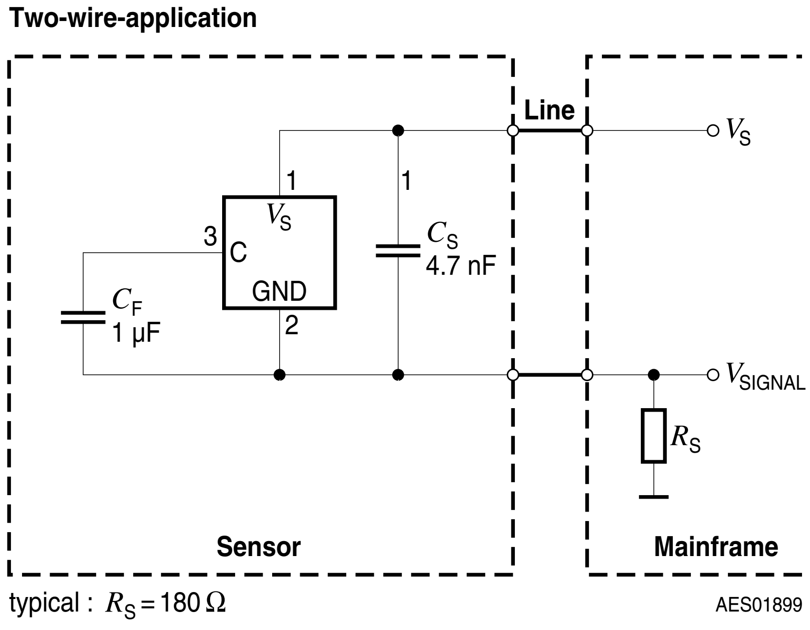


Figure 37
Test Circuitry for DIN 40839-1 Test

Table 3
Functional Status of TLE4923 according to DIN 40839-1 Test Levels

Test Pulse	Functional Status according to Test Levels			
	I	II	III	IV
1	C	C	C	C
2	B	B	B	B
3a	C	C	C	C
3b	C	C	C	C
4	C	C	C	C
5	see **Table 4**			

The load dump pulse 5 is investigated in more detail. The results are shown as a function of the pulse amplitudes V_S, the pulse duration t_d and the signal resistance R_S:

Table 4
Functional Status of TLE4923 according to DIN 40839-1 Pulse 5

V_S / V	t_d / ms	R_S / Ω	Class	COMMENT
45	400	180	C	
50	400	180	C	
55	400	180	C	
58	400	180	E	
60	200	180	C	
60	300	180	E	I_S increases → destruction
60	300	180	E	
65	100	180	E	
65	400	330	C	800 ms recovery time
82	400	330	E	
84	400	330	E	
110	200	330	E	I_S increases → destruction

Also for the TLE4923 the signal resitor 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 signal resistor.

EMC: Injection of Capacitive Line Transients (DIN 40839-3)

The test setup is as described in **Chapter 7.1.3**. The Hall IC is actuated with a magnetic coil (ΔB = 5 mT @ f = 200 Hz) and the supply line has a length of 2 m. Again the test circuitry in **Figure 38** is used. Missing pulses are the malfunction criteria. For all pulses and severity levels class A is achieved, i.e. no disturbance is measured. First spurious switching effects are observed for voltages larger than ± 1000 V, well above the levels of ± 60 V stated in the DIN standard.

EMC: Radiated Interference (DIN 40839-4)

This test is carried out in a TEM cell. The setup is described in **Chapter 7.1.7** (Electromagnetic Compatibility in Automotive Applications). Again the test circuit in **Figure 38** is used. The Results of the TEM measurement are shown in **Figure 38**. The TLE4923 IC performs practically over the whole frequency range without disturbance for differential fields down to 5 mT.

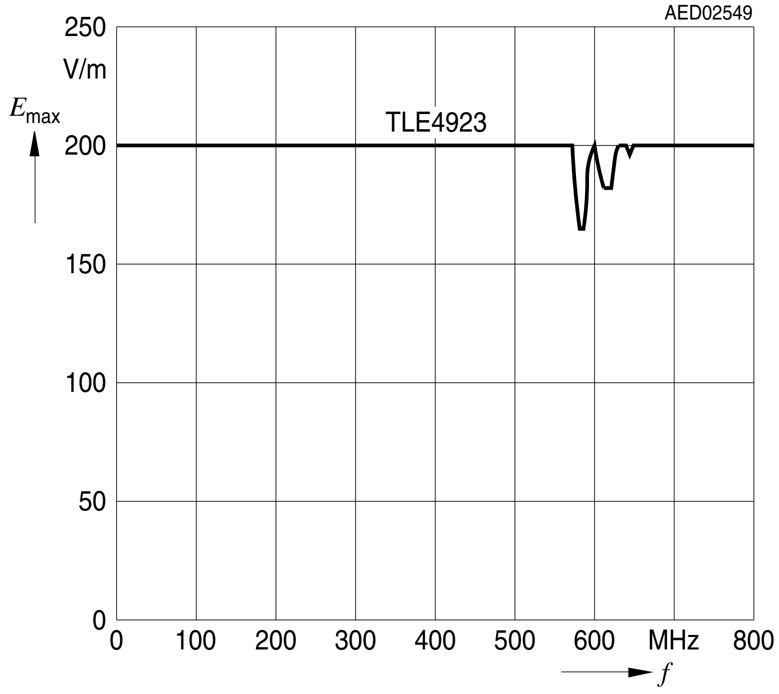


Figure 38
Results of the Radiated Interference Test with the TLE4923

Optimization of TLE4923 and Passive Circuitry for Improved EMI Performance

The following recommendation is the results of EMI measurements carried out on the device during in-house testing. It is referred to the application and test circuit in **Figure 37**.

Component values:

C_F = 470 nF – 1 μF	High pass filter capacitor
C_S = 4.7 nF	Additional HF shunt
R_S = 100 – 200 Ω	Signal resistor

Optimization points in detail:

1. Ground
   The reference point 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 TLE4923 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. Additional HF shunts
   Ideally arranged RF shunts C_S can further improve the EMI immunity. A larger C_S will improve the RF performance.

Signal Behavior for Different Dimensions of Toothed Gear Wheels

Since the Hall probe spacing of 2.5 mm of TLE4923 is identical to the one of TLE4921-5U, the investigations carried out with the TLE4921-5U also apply to TLE4923.

7.1.6 Electrical Tests and Application Circuit

- The sockets or integrated circuits must not be conducting any voltage when individual devices or assembled circuit boards are inserted or withdrawn, unless works' specifications state otherwise. Ensure that the test devices and power supplies do not produce any voltage spikes, either when being turned on and off in normal operation or if the power fuse blows or other fuses respond.
- When supplying bipolar integrated circuits with current, the negative voltage (– V_S or GND) has first to be connected. In general, an interruption of this potential during operations is not permissible.
- Signal voltages may only be applied to the inputs of ICs when or better after the supply voltage is turned on. They must be disconnected when or better before the supply voltage is turned off.
- Power supplies of integrated circuits are to be blocked as near as possible at the supply terminals of the IC. With bipolar ICs it is recommended to use a low-inductance electrolytic capacitor or at least a paralleled ceramic capacitor of 100 nF to 470 nF for example. Using ICs with high output currents, the necessary value of the electrolytic capacitor must be adapted to the test or application circuit. Transient behaviour and dynamic output resistance of the power supplies, line inductances in the supply and load circuit and in particular inductive loads or motors have to be considered. When switching off line inductances of inductive loads, the stored power has to be consumed externally, unless otherwise specified (e.g. by an electrolytic capacitor, diodes, Z-diodes or the power supply). Also a switching off of the supply voltage prior to the load rejection should be taken into account.
- ICs with low-pass characteristic of the output stages (e.g. PNP drivers or PNP/NPN end stages), normally need an additional external compensation at the output. This applies particulary to complex loads. The output of AF power amplifiers is compensated by the Boucherot element. In individual cases, bridge circuits only need a capacitance for bypassing the load. Depending on the application it is, however, also recommended to connect one capacitor from each output to ground.
- Observe any notes and instructions in the respective data sheets.

7.1.7 Electromagnetic Compatibility (EMC) in Automotive Applications

Electromagnetic compatibility is the ability of an electric device to work satisfactorily in an electromagnetic enviroment without any impermissible influence on this environment (e.g. DIN VDE 0870).

The DIN 40839 and the comparable ISO 7637 standards insure EMC in road vehicles and define several types of tests:

DIN 40839-1: Injection of supply line transients (test pulses) in 12 V onboard systems
DIN 40839-2: Injection of supply line transients (test pulses) in 24 V onboard systems
DIN 40839-3: Injection of capacitive line transients
DIN 40839-4: Radiated interference

DIN 40839-1/-2: Injection of Supply Line Transients

Table 5 summarizes the amplitudes of the different transients. The respective pulse profiles are defined in the standards. The battery voltages used are V_{batt} = 13.5 V (27 V) for a 12 V (24 V) on-board voltage supply. Since some of the pulses are generated with the so-called Schaffner Generator, it is sometimes referred to as Schaffner test pulses.

Table 5
Severity Level of Test Pulse for 12 V Supply Voltage (24 V Supply Voltage)

Test Pulse	Pulse Amplitude V_S in Volts for Severity Levels			
	I	II	III	IV
1	– 25 (– 50)	– 50 (– 100)	– 75 (– 150)	– 100 (– 200)
2	+ 25 (+ 25)	+ 50 (+ 50)	+ 75 (+ 75)	+ 100 (+ 100)
3a	– 25 (– 35)	– 50 (– 70)	– 100 (– 140)	– 150 (– 200)
3b	+ 25 (+ 35)	+ 50 (+ 70)	+ 75 (+ 140)	+ 100 (+ 200)
4	– 4 (– 5)	– 5 (– 10)	– 6 (– 14)	– 7 (– 16)
5	+ 26.5 (+ 70)	+ 46.5 (+ 113)	+ 66.5 (+ 156)	+ 86.5 (+ 200)

Table 6 lists the failure mode serverity classification that applies to DIN 40839 and ISO 7637.

Table 6
DIN 40839 and ISO 7637 Failure Mode Severity Classification

Class A	All functions of a device/system perform as designed during and after exposure to disturbance.
Class B	All functions of a device/system perform as designed during exposure: however, one or more of them can go beyond specified tolerance. All functions return automatically to within normal limits after exposure is removed. Memory functions shall remain Class A.
Class C	All functions of a device/system does not perform as designed during exposure but returns automatically to normal operation after exposure is removed .
Class D	All functions of a device/system does not perform as designed during exposure and does not return to normal operation until exposure is removed and the device/system is reset by simple “operator/use” action.
Class E	One or more functions of a device/system does not perform as designed during and after exposure and cannot be returned to proper operation without repairing or replacing the device/system.

DIN 40839-3: Injection of Capacitive Line Transients

This test is used to simulate capacitive coupling of burst pulses into control and data lines of electric devices. A so-called coupling clamp is used to generate the capacitive coupling. The setup as used for the measurements is shown in **Figure 39**.

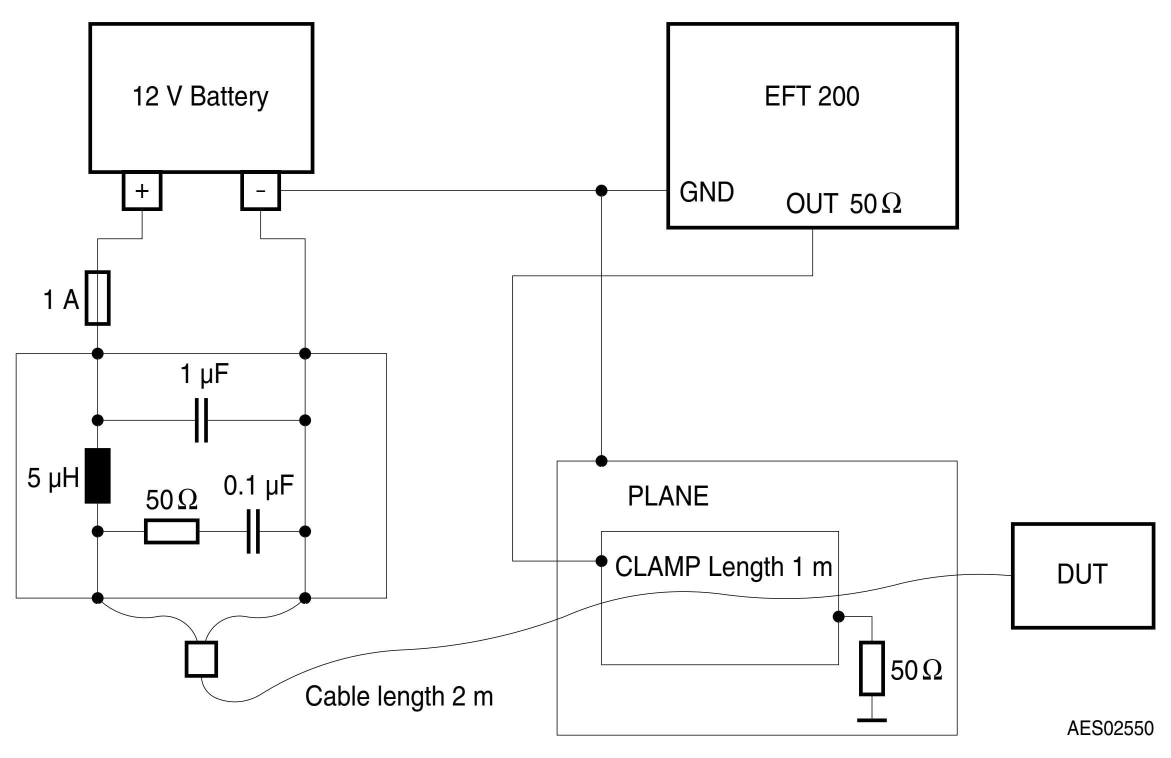


Figure 39
Coupling Clamp Measurement Setup (EFT 200: Pulse Generator)

The Hall IC (DUT: Device Under Test) is actuated with a magnetic coil (ΔB = 5 mT @ f = 200 Hz) and the supply line has a length of 2 m. Missing pulses are the malfunction criteria. **Table 7** shows the amplitudes of the capacitive pulses according to the DIN standard. Also in this test the severity classification in **Table 6** applies.

Table 7
Severity Level of DIN 40839-3 Test Pulses (12 V Supply Voltage)

Test Pulse	Pulse Amplitude V_S in Volts for Severity Levels			
	I	**II**	**III**	**IV**
1	– 7.5	– 15	– 22.5	– 30
2	+ 7.5	+ 15	+ 22.5	+ 30
3a	– 15	– 30	– 45	– 60
3b	+ 10	+ 20	+ 30	+ 40

DIN 40839-4: Radiated Interference

There are different tests for exposing an electric device to electromagnetic radiation. The two most common test methods for single components as e.g. Hall ICs are

- Stripline measurements
- Measurements in a TEM cell (Transverse Electro Magnetic)

For stripline measurements a signal generator provides an electromagnetic field (frequency typically 10 kHz … 1 GHz, E-field up to 250 V/m) between the two electrodes of an about 1 m long stripline. The wiring of the electric component is placed between the two electrodes of the stripline. The component itself is not exposed to the electromagnetic field. With this setup coupling of electromagnetic radiation into the wiring of the component is simulated. In a TEM cell the immunity of the component itself to electromagnetic radiation is measured. The component is placed in a homogeneous electromagnetic field, generated between the inner conductor of the TEM cell (septum) and is outer conductor (enclosure). **Figure 40** illustrates the structure of the TEM cell and the complete measurement setup, including the signal generator and the readout electronics.

Following the detailed measurement conditions for the differential Hall ICs TLE4923 and TLE4921-5U are summarized:

ElectromagneticField

- TLE4921-5U: Maximum carrier field 90 V/m, f = 10 kHz to 750 MHz, AM = 1 kHz, m = 80% (peak value 160 V/m)
- TLE4923: Maximum carrier field 110 V/m, f = 10 kHz to 750 MHz, AM = 1 kHz, m = 80% (peak value 198 V/m)

Hall IC Actuation

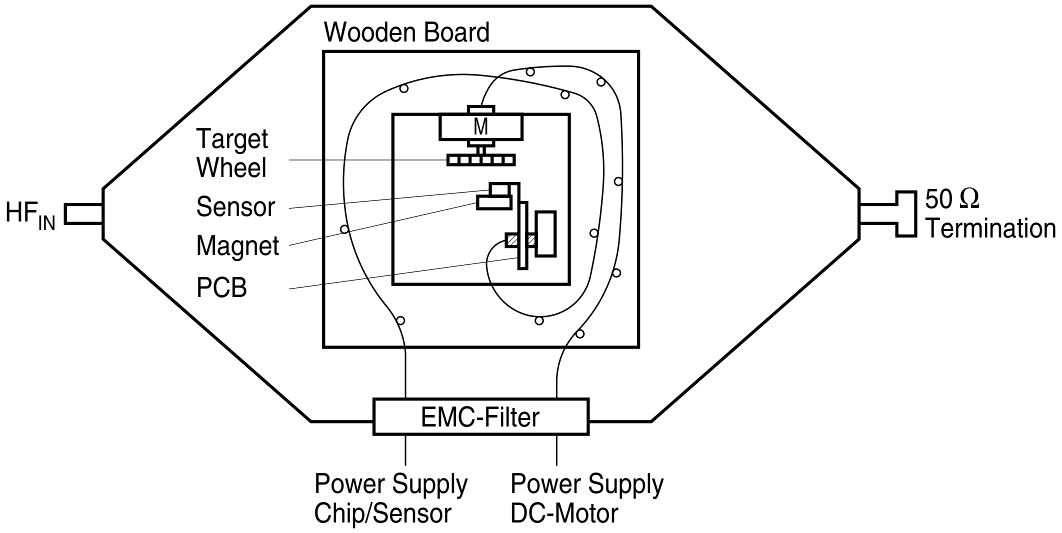
- TLE4921-5U: Target wheel, ΔB = 50 mT @ f = 100 Hz
- TLE4923: Magnetic coil for actuation, ΔB = 5 mT @ f = 200 Hz
- The position of the cables is fixed on a wooden board (thickness 20 mm). The cables must not touch the cell.

Malfunction Criteria and Detection

- TLE4921-5U: Missing pulses in the IC output
- TLE4923: Jitter of ± 0.2 ms is exceeded
- Detection: Oscilloscope and frequency counter

Measurement Method

Frequency sweeps in steps of 1 MHz at the highest E-field level, remaining one second at each frequency. In case of malfunction: Decrease of E-field to locate the minimum values.



M ... DC-Motor

f_B = 100 Hz, B = 100 mT ± 50 mT

Airgap between target wheel and "IC Housing": 0.5 mm

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Figure 40
Top View of the TEM Cell with Target Wheel powered by a DC Motor for Magnetic Actuation of the Hall IC Samples to be Tested.