

TLE4998

Configuration and Calibration of Linear Hall Sensor

User's Manual

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1 Scope

This document is valid for all TLE4998 variants and derivatives. It gives a detailed description of the configuration and calibration procedure, which is recommended to configure the TLE4998 for optimum accuracy in a sensing application.

2 TLE4998 Signal Processing

The TLE4998 uses a full digital signal processing concept. Analog values from the Hall probe are directly converted to raw digital signals by the Hall ADC and then compensated and processed in the digital signal processing unit (DSP) using configuration parameters stored in the EEPROM, temperature data acquired by an integrated temperature sensor and stress data acquired by an integrated stress sensor. A configurable second-order temperature polynomial is implemented to compensate the thermal reduction of the remanent magnetic flux of a permanent magnet used in a position sensing application. Additionally, an application-specific output characteristic can be set by configuring the EEPROM parameters Gain and Offset.

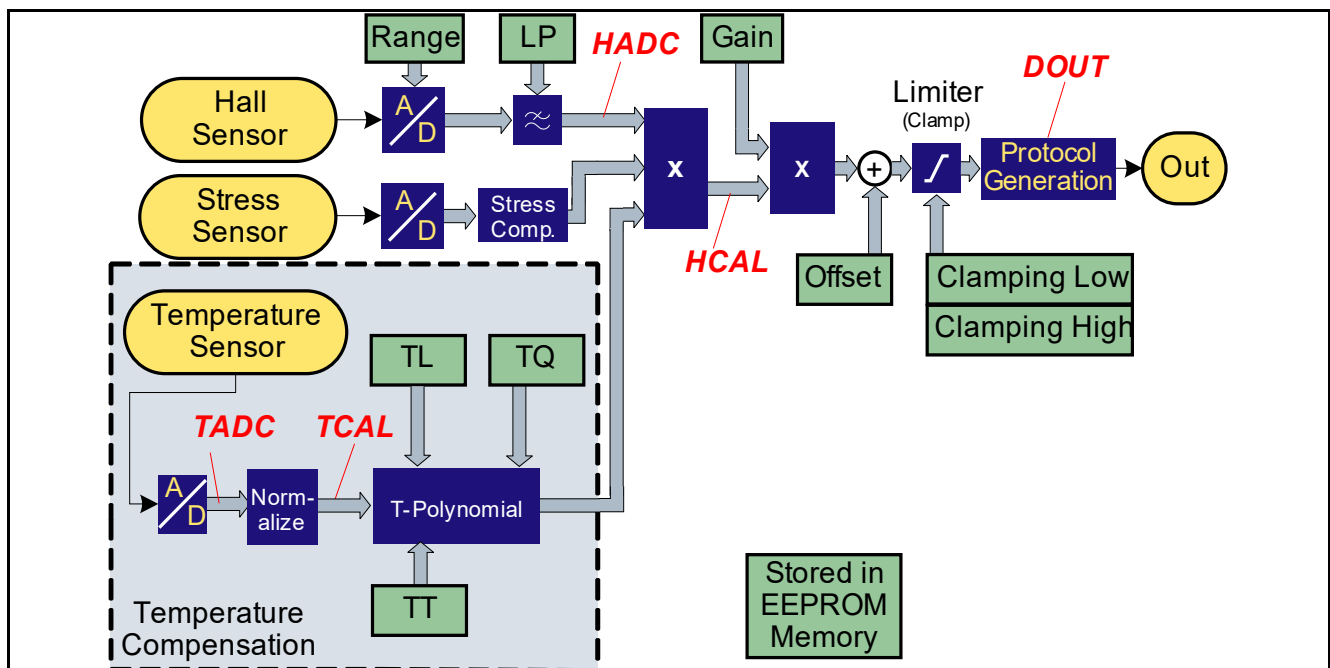


Figure 2-1 Signal Flow Diagram of the TLE4998

Figure 2-1 shows the signal flow diagram for temperature compensation and output characteristic in the DSP, and the influence of the relevant configuration parameters stored in the EEPROM. The Hall signal is processed in the following sequence of steps:

1. The analog Hall signal is converted by the Hall ADC, which operates at the configured magnetic range setting.
2. The digital value is filtered by a digital low-pass filter, which operates at a configurable filter frequency given by the "LP filter"-setting. The output of the filter is stored in the HADC register.
3. The HADC value is multiplied by the temperature compensation polynomial. The first order (TL) and second order (TQ) coefficients of the polynomial are configurable. The third order coefficient (TT) is fixed.
4. The value is multiplied by the stress compensation coefficient and the result is stored in the HCAL register. The integrated stress compensation is pre-configured by Infineon and does not require any user adaptation.
5. The HCAL value is multiplied by the configured gain value.
6. The configured offset value is added to the HCAL value.
7. The digital Hall value is clamped according to the configured upper and lower clamping limits. The output value of the clamping stage is stored in the DOUT register.
8. An output protocol is generated from the resulting DOUT value and transmitted on the OUT pin.

3 TLE4998 Programming

3.1 Programmer Connection

Figure 3-1 shows the connection of the TLE4998 to a programmer. The pins VDD and OUT of the sensor IC are used for the digital programming interface as described in **Table 3-1** (See datasheet of corresponding TLE4998 type for pinout).

Note: It is possible to sequentially program multiple sensors that share the same supply voltage connection, as long as they do not share the same OUT connection as well.

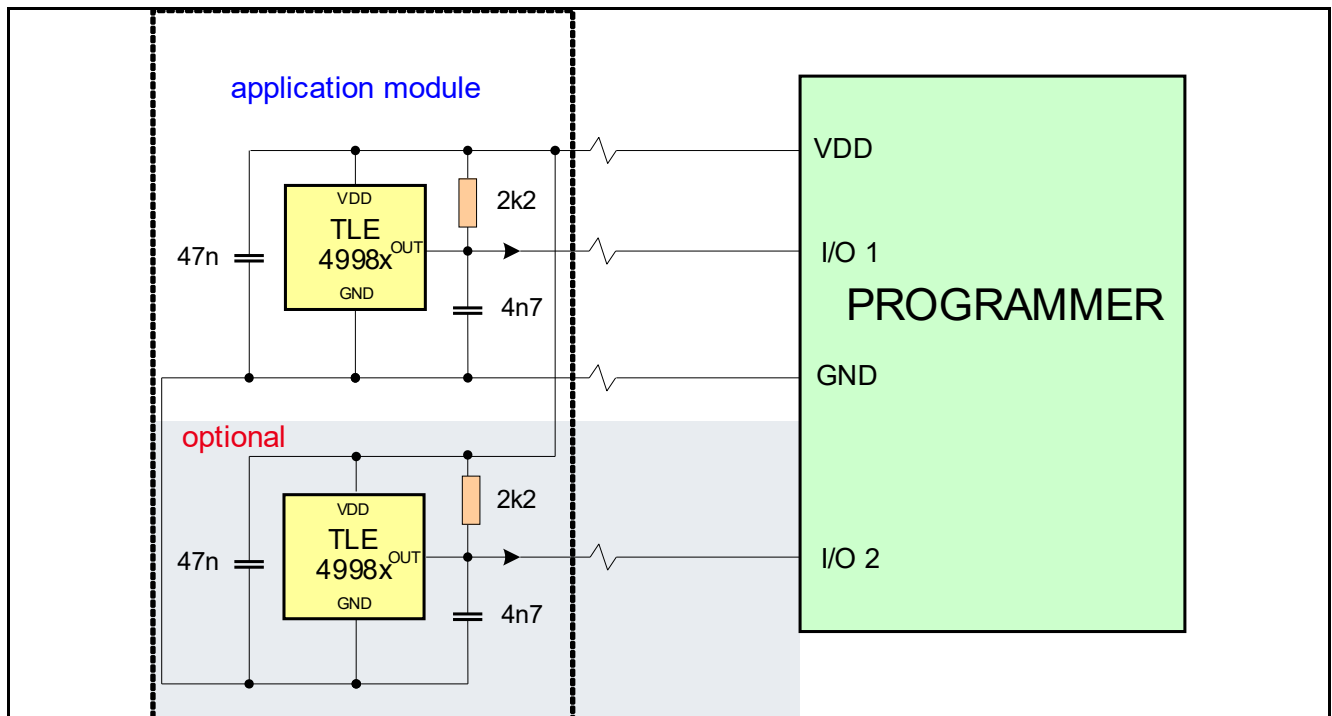


Figure 3-1 Connection of TLE4998 to Programmer

Table 3-1 Pin Functions for Programming Interface

Pin	Programming Function
TST	Test pin (no functionality, connection to GND is recommended)
VDD	Programming interface clock
GND	Ground
OUT	Programming interface data I/O and V

3.2 Programming Interface

3.2.1 Communication Scheme

The digital programming interface uses specific frames, which can have one of the two following functions:

- Command frames contain a specific task (e.g. read/write data, select EEPROM programming etc.) and a corresponding address
- Data frames contain a 16 bit data value sent to or received from the device - these frames can only follow a proper command frame for reading or writing data

A valid frame has the following properties:

- A frame consists of 21 bits in total
- A bit is shifted in or out via the output line with a rising clock edge on the supply line
- A frame always starts and ends with a '1' (frame bits)
- The LSB of a frame transmitted to the sensor is shifted in first
- The LSB of a frame replied by the sensor is shifted out first
- The whole frame sent to the device, including frame bits, is protected with an even positional and an odd positional parity bit

The first frame sent has to be a valid command to activate the interface mode and it has to be sent within 19ms after power up. As an additional protection, the device does not deactivate its output stage during this transmission (using 21 clock pulses) as shown in **Figure 3-2**. This means that the interface driver of the programmer needs to overrule the open drain output stage of the sensor during this initial transmission.

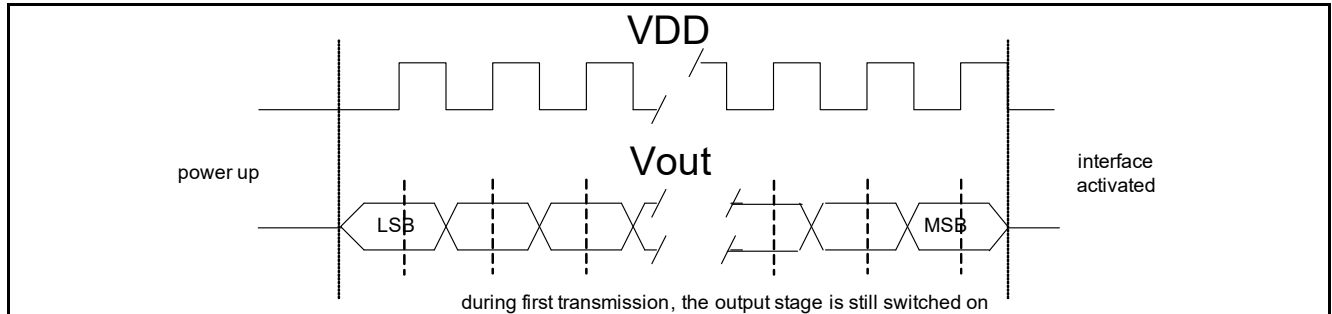


Figure 3-2 First Frame Transmission to the Sensor

Attention: Overruling Vout requires a strong driver on the programmer, since the OUT line must be driven to low levels close to GND for any "0"-bit and close to VDD for any "1"-bit in order to ensure a proper communication with the sensor.

After the first frame, to avoid additional power consumption in the output stage of the device, the internal driver is deactivated in programming mode while the sensor is receiving a frame. It is activated again after completion of the transmission. This is illustrated in **Figure 3-3**.

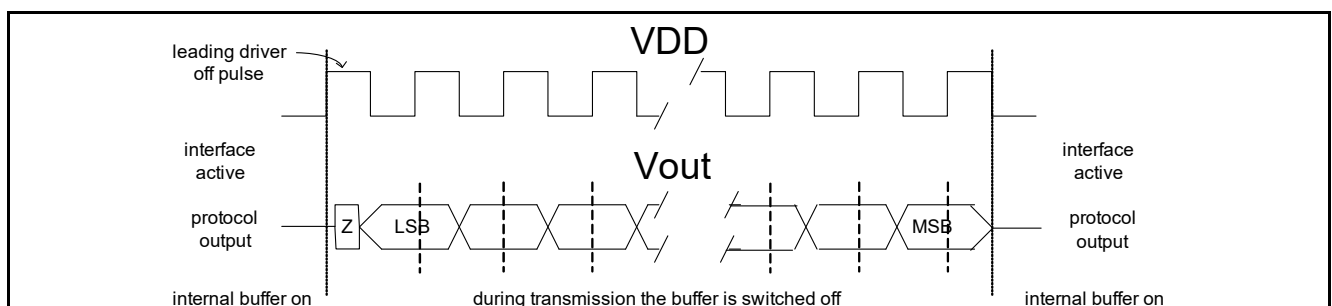


Figure 3-3 Further Frame Transmission from the Programmer to the Sensor (Write Access)

In case of a wrong command or data frame, the interface is immediately locked and the device falls back to its normal application mode. The read access to the device is triggered by clock pulses on the supply line as shown in [Figure 3-4](#). The timing of read and write accesses is described in [Chapter 3.2.4](#).

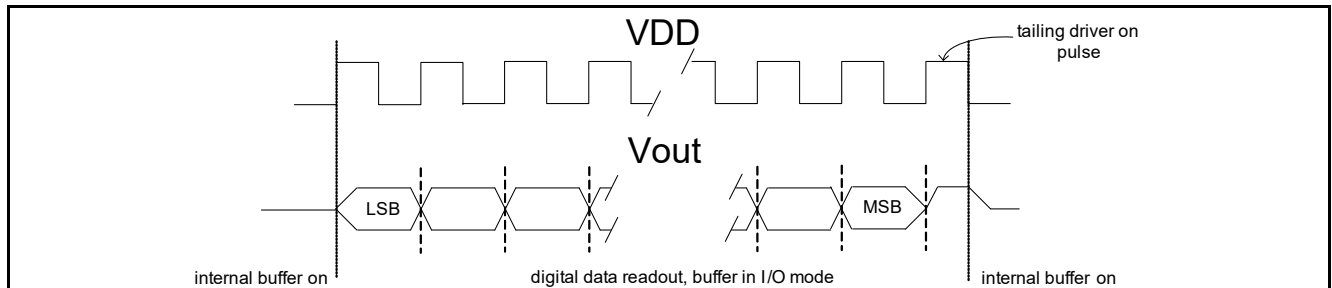


Figure 3-4 Frame Transmission from the Sensor to the Programmer (Read Access)

3.2.2 Command Frame

The structure of a command frame is shown in [Figure 3-5](#). Available commands are given in [Table 3-2](#). The parity bits PE (bit 17) and PO (bit 18) have to be set in the following way (bit 0 is the LSB, bit 20 is the MSB):

$$\text{bit0 XOR bit2 XOR bit4 XOR } \dots \text{ XOR bit20} = 0$$

$$\text{bit1 XOR bit3 XOR bit5 XOR } \dots \text{ XOR bit19} = 0$$

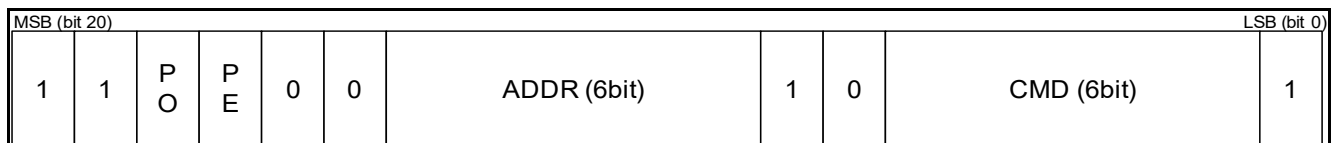


Figure 3-5 Command Frame Structure

Table 3-2 List of Available Commands

Command	Bits (MSB...LSB)	Function
0 _H	000000	Leave programming mode ¹⁾
1 _H	000001	Single data readout from given address without increment (sensor response: one data frame)
2 _H	000010	Continuous data readout from given address without increment (continuous readout can only be stopped by external supply reset)
3 _H	000011	Data readout from given address with increment (readout finishes when address "xxx111 _B " is reached)
9 _H	001001	Single data write to given address without increment (followed by one data frame)
A _H	001010	Continuous data write without increment (finished by sending another command frame)
B _H	001011	Data write to given address with increment (followed by multiple data frames; finishes at address "xxx111 _B " or by sending another command frame)
C _H	001100	Enable EEPROM write mode (programs "1"-bits) ¹⁾²⁾
D _H	001101	Enable EEPROM erase mode (programs "0"-bits) ¹⁾²⁾
E _H	001110	Enable EEPROM margin check mode (programs level check) ¹⁾³⁾
F _H	001111	EEPROM refresh (update EEPROM registers) ¹⁾

- 1) not to be followed by any data frame
- 2) followed by application of a programming pulse
- 3) followed by application of a margin voltage level before the last clock pulse falling edge

3.2.3 Data Frame

The structure of a data frame sent to the device is shown in **Figure 3-6**. The parity bits PE (bit 17) and PO (bit 18) have to be set in the same way as for the command frame (bit 0 is the LSB, bit 20 is the MSB):

$$\text{bit0 XOR bit2 XOR bit4 XOR ... XOR bit20} = 0$$

$$\text{bit1 XOR bit3 XOR bit5 XOR ... XOR bit19} = 0$$

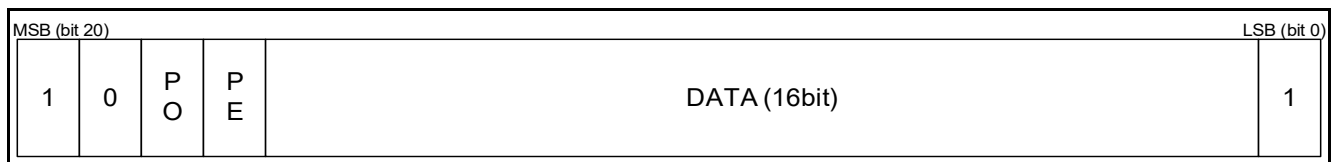


Figure 3-6 Data Frame to Sensor

Figure 3-7 shows a the structure data frame received from the sensor. Instead of a zero bit followed by two parity bits, the least significant 3 bits of the address used for the readout are transmitted together with the data. This allows to check the plausibility of the received data.

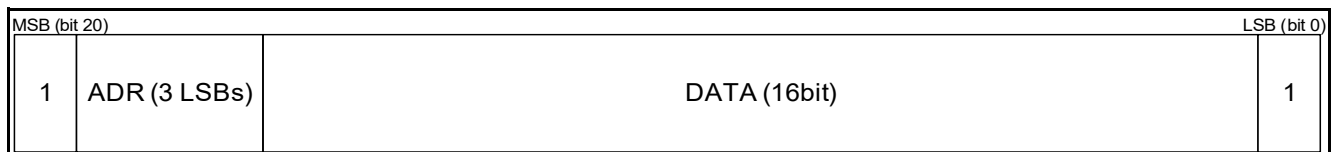


Figure 3-7 Data Frame from Sensor

3.2.4 Interface Specification

Table 3-3 specifies the operating conditions of the programming interface, which shall not be exceeded in order to ensure correct operation of the TLE4998 during programming. All specified parameters refer to these operating conditions, unless otherwise noted.

Table 3-3 Operating Range of the Programming Interface

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Supply voltage	V_{DD}	4.5	–	5.5	V	–
Supply buffer capacitance	C_S	47	–	1000	nF	V_{DD} to GND
Load capacitance	C_L	–	–	8	nF	OUT to GND
Ambient temperature	T_{PRG}	10	–	60	°C	during programming
Number of programming cycles	N_{PRG}			10	Cycles	Programming is allowed only at start of lifetime
Programming time	t_{PRG}	–	100	–	ms	For complete memory
Programming start time	t_{PRG_START}	–	–	19	ms	To start programming mode, a first read command shall be sent within this time window after power-up

The specification for timings and electrical levels of the programming interface is shown in [Table 3-4](#). The meaning of the timing parameters is illustrated in [Figure 3-8](#).

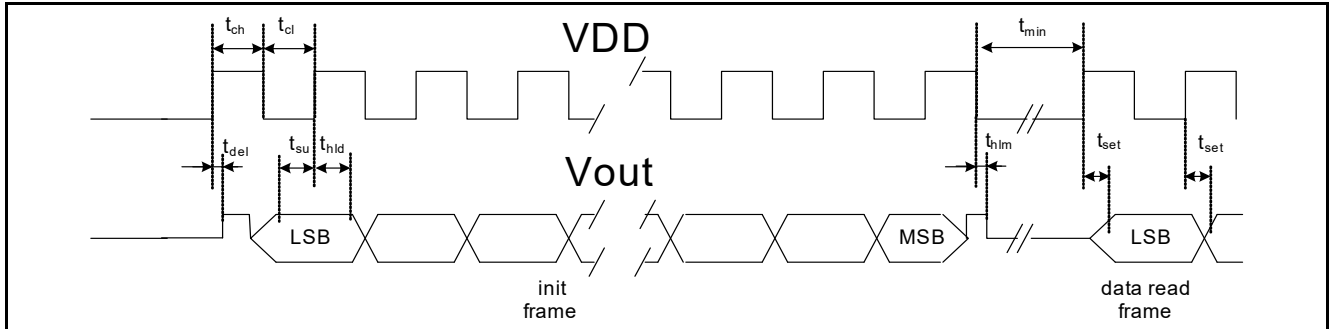


Figure 3-8 Frame Timing

Table 3-4 Electrical and Timing Specification of the Programming Interface

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
V_{DD} clock high level	$V_{DD,CLKHI}$	9	10	11	V	specification of V_{DD} operating range does not apply to clock
V_{DD} clock low level	$V_{DD,CLKLOW}$	4.8	5	5.2	V	
OUT data out high level	$V_{O,OHIGH}$	–	–	–	V	refer to open-drain specification in data sheet
OUT data out low level	$V_{O,LOW}$	–	–	–	V	
OUT data in high level	$V_{O,IHIGH}$	50%	–	100%	of V_{DD}	
OUT data in low level	$V_{O,LOW}$	-0.2	0.0	0.1	V	
OUT data input current	I_O	-5	–	5	mA	
V_{DD} clock high time	t_{CH}	2.5	50	–	μ s	
V_{DD} clock low time	t_{CL}	2.5	50	–	μ s	
Data in setup time	t_{SU}	1.5	2.0	–	μ s	to rising V_{DD}
Data in hold time	t_{HLD}	2.3	3.0	–	μ s	after rising V_{DD}
Data out settling time	t_{SET}	–	1.0	1.7	μ s	after rising V_{DD}
Time between frames	t_{MIN}	10.0	–	–	μ s	

In order to permanently store a programmed parameter set to the EEPROM, the “EEPROM erase” and “EEPROM write” commands shall be sent, followed by a programming pulse. [Figure 3-9](#) shows the timing of the programming pulse.

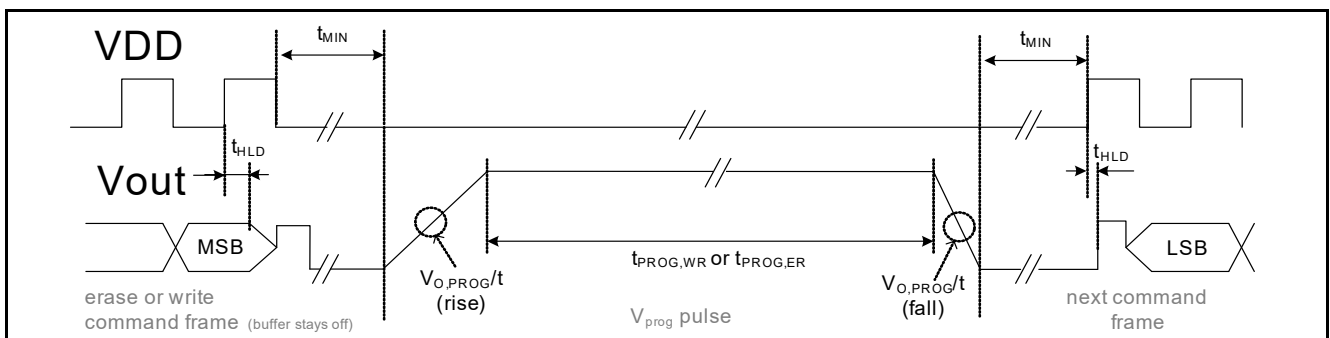


Figure 3-9 Programming Pulse Timing

After programming, a margin check is necessary to test the stability of the programmed data. The margin check is initiated by an "EEPROM margin check" command followed by a margin voltage.

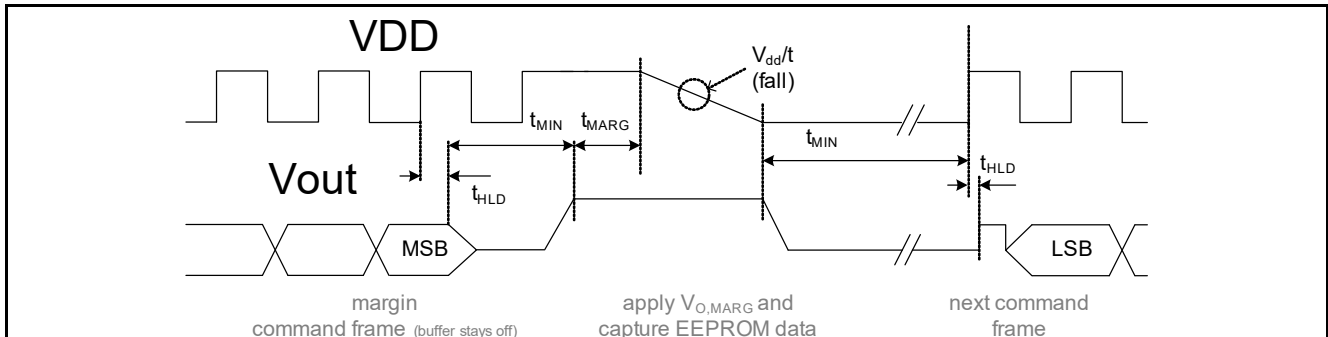


Figure 3-10 Margin Check Timing

The margin voltage is varied during subsequent steps within the threshold margin level range. A too low margin voltage value indicates a too short programming pulse duration or a too low programming voltage. A too high margin voltage value indicates a too long programming pulse duration or a too high programming voltage.

Table 3-5 gives the electrical and timing specifications of the programming pulse and the margin voltage check procedure.

Table 3-5 Electrical and Timing Specification of the Programming Pulse and Margin Voltage

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
OUT data input current	I_O	0	–	5	mA	during application of programming pulse or margin voltage
OUT margin level	$V_{O,MARG}$	-0.1	–	7	V	
Threshold margin level	V_{TH}	2.23	–	4.5 0.4	V V	check "1" check "0"
Margin setup time	t_{MARG}	200	–	–	μ s	
V_{DD} slope for margin	V_{DD}/t	-10	–	-1.25	V/ μ s	
OUT program level	$V_{O,PROG}$	19.2	19.3	19.4	V	
OUT program slope (rise) ¹⁾	$V_{O,PROG}/t$	–	–	2	V/ μ s	time to reach $V_{O,PROG}$ shall not exceed 50 μ s
OUT program slope (fall) ¹⁾	$V_{O,PROG}/t$	-10	–	–	V/ μ s	
OUT write time	$t_{PROG,WR}$	9.9	10.0	10.1	ms	
OUT erase time	$t_{PROG,ER}$	79.2	80.0	80.8	ms	

1) faster slope may lead to permanent damage of the EEPROM.

3.3 Register Map

Table 3-6 shows the internal registers of the TLE4998 (compare also [Figure 2-1](#)).

Table 3-6 TLE4998 Register Map

Address	Symbol	Function	R/W
00 _H	DOUT	Data out value (16bit unsigned, with clamping)	read only
05 _H	HCAL	Calibrated Hall value	read only
06 _H	TCAL	Calibrated temperature value, including reference temperature T ₀	read only
07 _H	SCAL	Calibrated stress value	read only
0A _H	HADC	Uncalibrated Hall ADC value	read only
0B _H	TADC	Uncalibrated temperature ADC value	read only
0C _H	SADC	Uncalibrated stress ADC value	read only
0F _H	STATUS	Status register	read only
10 _H ...1A _H	EEPROM	EEPROM registers (see Chapter 3.4)	read/write
1B _H	TEST	Test mode register	read/write

Note: To access the registers (except STATUS, HADC, TADC, SADC, DOUT and TEST), the digital signal processing unit (DSPU) has to be disabled first via the TEST register.

DOUT

This value is the 16 bit unsigned decimal result applied to the internal protocol generation for the open drain output stage. It includes the clamping limits if programmed. The value range is from decimal 0 to 65535.

HCAL

This register contains the temperature- and stress-compensated magnetic measurement as a 16bit signed value. This value is in the range of +/- 30000.

TCAL

This register contains a 16 bit signed value and delivers the current junction temperature of the device. The junction temperature in °C is calculated from the register value by: $T_j = (T_CAL/16+48)$ [°C].

SCAL

This register contains the calibrated stress measurement value used for the stress compensation.

HADC

This register contains a 16bit signed value that corresponds to the raw Hall cell measurement value. This value is in the range of +/- 20000.

TADC

This register contains a 15bit unsigned raw temperature value.

SADC

This register contains the raw stress measurement value.

STATUS

The content of the status register is shown in [Figure 3-11](#).

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	LSB
ROMSIG4	ROMSIG3	ROMSIG2	ROMSIG1	ROMSIG0	HWver2	HWver1	HWver0	perr_col	perr_more	perr_adr3	perr_adr2	perr_adr1	perr_adr0	LOCKED	CRC ok	

Figure 3-11 Status Register

- CRC ok has to be “1”, otherwise the DSP built-in self-test was failed and the device is defective
- LOCKED has to be “0” as long as the lockbits of the EEPROM are not programmed. This bit changes to “1” in the next power cycle (external reset) after locking the device.
- perr_adr has to be on address F_H (“1111_B”), otherwise it shows the first EEPROM address where the internal parity check failed.
- perr_more has to be “0”, otherwise more than one EEPROM address has a parity error.
- perr_col has to be “0”, otherwise one or more EEPROM columns have a parity error.
- HWver contains the hardware version. It is “000_B” for the TLE4998P (all versions) and the TLE4998S3, S4 and S3C. It is “001_B” for the TLE4998C3, C4, C8(D) design step B1 and the TLE4998S8(D). It is “002_B” for the TLE4998C8(D) design step B2.
- ROMSIG has to be 15_H, otherwise the DSP ROM is not valid and the device is defective.

For a sensor that is operating correctly, the status register is equal to A83D_H (TLE4998P all types, TLE4998S3, S4, and S3C), A93D_H (TLE4998C all types with design step B1, TLE4998S8(D)) and AA3D_H (TLE4998C8(D) design step B2), respectively.

TEST

The content of the test register is shown in [Figure 3-12](#). All bits are “0” after reset. All bits not described or used shall be kept at “0”.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	LSB
0	0	0	0	DSP stop	DSP off	REF off	0	PROTOCOL off	FEC off	Margin zero on	0	0	0	0	0	

Figure 3-12 Status Register

- “Margin zero on” is used to select the margin test mode. It is set to ‘1’ for testing the EEPROM threshold voltages of cells programmed to ‘0’, and it is set to ‘0’ for testing the EEPROM threshold voltages of cells programmed to ‘1’.
- “FEC off” switches off the error correction of the EEPROM. This bit has to be set when reading the EEPROM content.
- “REF off” switches off the automatic (cyclic) refresh performed by the DSP to actualize the EEPROM registers from the EEPROM cells. This bit has to be set when writing new values to the EEPROM registers.
- “DSP off” switches off the signal processing unit (DSP). This bit has to be set prior to access the internal register values via the interface (HCAL, TCAL, SCAL and EEPROM).
- “DSP stop” has to be set prior to switching the DSP off (as a separate command) before reading out the calculated data HCAL, TCAL, and/or SCAL. This allows the DSP to finish the calculation of the current sample and all values in the RAM are consistent.

- “PROTOCOL off” can be set together with “DSP off”, if it is desired to get correct protocol output after “DSP off” and “PROTOCOL off” are cleared again. Otherwise, a reset is necessary to get correct protocol output.

3.4 EEPROM Map

The EEPROM registers 10_H to 1A_H mirror the content of the TLE4998's EEPROM. The EEPROM map is different for the TLE4998 types.

Figure 3-13 shows the content of the EEPROM registers for the TLE4998P (all types) and the TLE4998S3, S4, and S3C.

Figure 3-14 shows the content of the EEPROM registers for the TLE4998C (all types) and the TLE4998S8(D).

ADDR	Description	15	14	13	12	11	10	09	08	07	06	05	04	03	02	01	00
10 _H	Parity of each column	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c
11 _H	IC lock high, clamping high/low	P _i	LH	CH - Clamping high (bit 6...0)						CL - Clamping low (bit 6...0)							
12 _H	Gain	P _i	G - Gain (bit 14...0)														
13 _H	Offset	P _i	OS - Offset (bit 14...0)														
14 _H	ID, precal status, predivider, TQ value	P _i	ID	PC	Prediv (bit 3...0)				TQ - quadratic temperature coefficient (bit 7...0)								
15 _H	Bandwidth, Range, TL value, IC lock low	P _i	BW (bit 2...0)			R (1...0)		TL - linear temperature coefficient (bit 8...0)							LL		
16 _H	TT value (do not modify)	P _i	Reserved - do not modify										TT - cubic temp. coefficient (4...0)				
17 _H	Reserved	P _i	Reserved - do not modify														
18 _H	Reserved	P _i	Reserved - do not modify														
19 _H	Reserved	P _i	Reserved - do not modify														
1A _H	Reserved	P _i	Reserved - do not modify														

Figure 3-13 EEPROM Map of TLE4998P (all types), TLE4998S3, S4 and S3C.

The fields marked in red are configuration parameters for the sensor hardware. Those marked in yellow are used by the DSP algorithms for signal processing. The blue and cyan fields are parity bits for the corresponding lines and columns used by the internal forward error correction (FEC). All parameters are unsigned integer values. The reserved fields marked in white shall not be changed.

The functional description of the configuration and calibration parameters in the EEPROM map is given in [Chapter 4](#).

Parity Bits

The parity P_c of each column (including the precalibration ranges) is even for even bit positions (bit0=LSB, bit2, bit4, ... bit14) and the parity P_c for all odd columns (bit1, bit3, ... bit13) is odd, except for the parity P_c for the column at bit15 (MSB), which is even. The parity P_i of every EEPROM line (address 0x11 ... 0x1A) is always odd.

Note: Before accessing the EEPROM, the forward error correction (FEC) shall be disabled via the TEST register.

Precalibration Bit

The "PC" bit in line 14_H shall be set by the system integrator when changing the EEPROM content of the device for the first time. Thereby it is possible to identify devices which still have precalibrated settings from the Infineon factory calibration (PC = 0 means precalibrated device, PC = 1 means user calibrated device).

Lock Bits

LH and LL are lock bits (LH locked if '1', LL locked if '0'). If either LH, LL or both are set to locked state, the programming interface cannot be accessed anymore.

ADDR	Description	15	14	13	12	11	10	09	08	07	06	05	04	03	02	01	00
10 _H	Parity of each column	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c	P _c
11 _H	IC lock high, clamping high/low	P _l	LH	CH - Clamping high (bit 5...0)						CL - Clamping low (bit 5...0)						F (1...0)	
12 _H	Gain	P _l	G - Gain (bit 14...0)														
13 _H	Offset	P _l	OS - Offset (bit 14...0)														
14 _H	ID, precal status, predivider, TQ value	P _l	ID	PC	Prediv (bit 3...0)				TQ - quadratic temperature coefficient (bit 7...0)								
15 _H	Bandwidth, Range, TL value, IC lock low	P _l	BW (bit 2...0)			R (1...0)		TL - linear temperature coefficient (bit 8...0)								LL	
16 _H	Prot, TT value (do not modify)	P _l	Prot (1...0)		Reserved - do not modify							TT - cubic temp. coefficient (4...0)					
17 _H	Reserved	P _l	Reserved - do not modify														
18 _H	Reserved	P _l	Reserved - do not modify														
19 _H	Reserved	P _l	Reserved - do not modify														
1A _H	Reserved	P _l	Reserved - do not modify														

Figure 3-14 EEPROM Map of TLE4998C (all types), and TLE4998S8(D).

3.5 Programming Flow

The programming flow diagram in [Figure 3-15](#) shows the procedural steps to setup the EEPROM content and to program new values (EEP_NEW). EEP_PROG means the intermediate values stored in the EEPROM register and EEP_OLD means the initial (old) EEPROM content.

Flowchart description:

1. Switch on the device.
2. Send an initial command (status register readout):
Check that the status is valid (Status register = A83D_H, A93D_H or AA3D_H compare [Chapter 3.3](#)), if not, do not continue and check the failure.
3. Set the register bits FECoff = 1, DSPoff = 1, REFOff = 1 (allows EEPROM access).
4. Read out the EEPROM content to an array EEP_OLD (store also for reference purpose and traceability)
In parallel: Prepare the data that shall be programmed as an array EEP_NEW.
5. Calculate the bits to be cleared from EEP_OLD to EEP_NEW as EEP_PROG array.
6. Write the EEPROM content from the EEP_PROG array to the EEPROM registers

7. Send the EEPROM erase command
Apply an erase programming pulse on the output pin (see [Chapter 3.2.4](#)).
8. Calculate the bits to be set from EEP_OLD to EEP_NEW as EEP_PROG array.
9. Write the EEPROM content from the EEP_PROG array to the EEPROM registers.
10. Send the EEPROM write command
Apply a write programming pulse on the output pin (see [Chapter 3.2.4](#)).
11. Send the EEPROM margin command
During the falling edge of the margin pulse on V_{DD} , apply $V_{O,MARG}$ on the output (see [Chapter 3.2.4](#)).
12. Read out the EEPROM content to the array EEP_PROG.
13. Verify the EEP_PROG data against EEP_NEW to check the programming (no bits flipped)
Optionally, steps 11 to 13 can be looped to find the exact margin threshold voltage.
If the margin threshold voltage is too low, do not continue and check the failure.
14. Check the status register again.

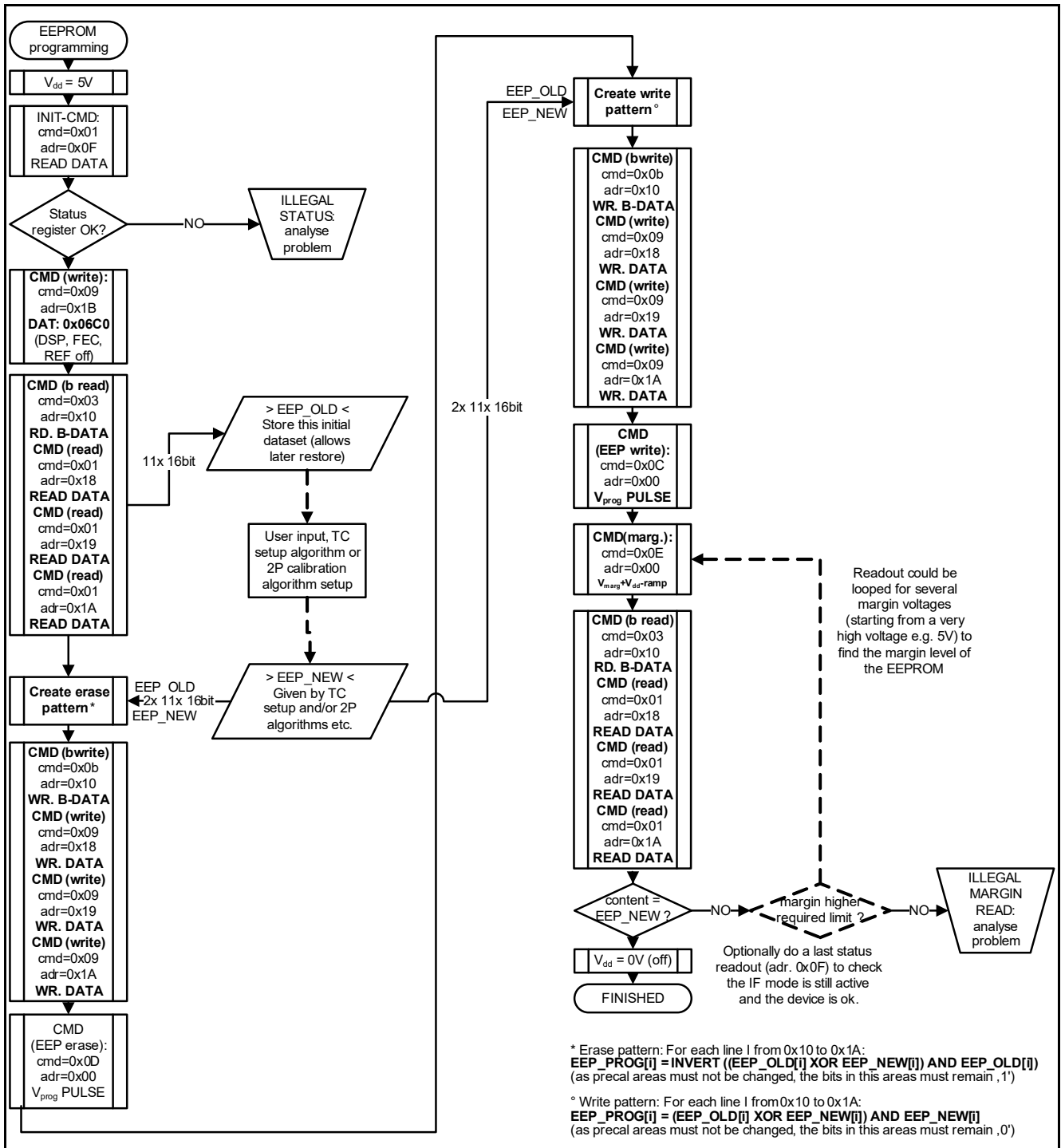


Figure 3-15 Programming Flow

The following chapters give a more detailed description of individual steps of the programming flow:

3.5.1 Readout of the EEPROM Content

The following steps are used to readout the EEPROM and store the content in an array:

1. Send a block read command (EEPROM data readout: Command 03_H, Address: 10_H).
2. Read the first 8 data words of the EEPROM and store it in an array.
3. Send a read command (EEPROM data readout: Command 01_H, Address: 18_H).

4. Read the 9th data word of the EEPROM and store it in an array.
5. Send a read command (EEPROM data readout: Command 01_H, Address: 19_H).
6. Read the 10th data word of the EEPROM and store it in an array.
7. Send a read command (EEPROM data readout: Command 01_H, Address: 1A_H).
8. Read the 11th data word of the EEPROM and store it in an array.

3.5.2 Setting the EEPROM Content

The following steps are used to set the EEPROM content with data from an array:

1. Send a block write command (EEPROM data write: Command 0B_H, Address: 10_H).
2. Send the first 8 data words from the array to the EEPROM.
3. Send a write command (EEPROM data write: Command 09_H, Address: 18_H).
4. Send the 9th data word from the array to the EEPROM.
5. Send a write command (EEPROM data write: Command 09_H, Address: 19_H).
6. Send the 10th data word from the array to the EEPROM.
7. Send a write command (EEPROM data write: Command 09_H, Address: 1A_H).
8. Send the 11th data word from the array to the EEPROM.

3.5.3 Calculation of Bits to Erase

The EEP_PROG array for the erase procedure is calculated from the old EEPROM content EEP_OLD and the new EEPROM content EEP_NEW in the following way:

For each data word i : $EEP_PROG[i] = \text{INVERT} ((EEP_OLD[i] \text{ XOR } EEP_NEW[i]) \text{ AND } EEP_OLD[i])$

Table 3-7 shows an example of a calculated erase mask.

Table 3-7 Erase Array Example

EEP_OLD	0101010101010101
EEP_NEW	0101110001010101
EEP_PROG	1111111011111111

3.5.4 Calculation of Bits to Write

The EEP_PROG array for the write procedure is calculated from the old EEPROM content EEP_OLD and the new EEPROM content EEP_NEW in the following way:

For each data word i : $EEP_PROG[i] = (EEP_OLD[i] \text{ XOR } EEP_NEW[i]) \text{ AND } EEP_NEW[i]$

Table 3-7 shows an example of a calculated erase mask.

Table 3-8 Write Array Example

EEP_OLD	0101010101010101
EEP_NEW	0101110001010101
EEP_PROG	0000100000000000

3.5.5 Margin Voltage Check

The threshold voltage of EEPROM cells is dependent on the programming voltage and programming pulse length. For reliable programming the programming pulse has to be kept within the specification (**Table 3-5**) at the sensor interface. The margin command can be used to check the threshold voltages of the programmed cells:

To check the cells programmed to '1', a voltage $V_{O,MARG}$ is applied after the margin check command (Command E_H). For EEPROM cells with a threshold voltage smaller than the applied $V_{O,MARG}$, a '0' will be stored to the

EEPROM registers, for those with a higher threshold voltage, a '1' will be written. By sweeping the applied $V_{O,MARG}$, the actual threshold voltages of each EEPROM cell can be identified.

In order to check the threshold voltages of EEPROM cells programmed to '0', it is necessary to activate the "Margin zero on" bit in the TEST register before sending the margin check command. Also for the '0' cells, the actual threshold voltages of each EEPROM cell can be identified, by sweeping the applied $V_{O,MARG}$.

4 Configuration & Calibration Parameters

This chapter describes the configuration and calibration parameters that can be set in the EEPROM of the TLE4998 (see EEPROM map, [Chapter 3.4](#))

4.1 Magnetic Field Range - R

The working range of the magnetic field defines the input range of the A/D converter. It is always symmetrical around the zero field point. Any two points in the magnetic field range can be selected to be the end points of the output value. The output value is represented within the range between the two points.

In the case of fields higher than the range values, the output signal may be distorted.

Table 4-1 Range Setting

Parameter R	Range	Nominal Range in mT ¹⁾
3	Low	±50
1 ²⁾	Mid	±100
0	High	±200

1) Absolute accuracy of range values is not specified.

2) Setting R = 2 is not used, internally changed to R = 1.

4.2 Gain Setting - G

The overall sensitivity is defined by the range and the gain setting. The output of the ADC is multiplied by the Gain value. The Gain value is given by:

$$Gain = (G - 16384) / 4096 \quad (4.1)$$

Table 4-2 Gain

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Gain range	Gain	- 4.0	–	3.9998	–	1)2)
Gain quantization steps	ΔGain	–	244.14	–	ppm	Corresponds to 1/4096

1) For Gain values between -0.5 and +0.5, the numerical accuracy decreases.

To obtain a flatter output curve, it is recommended to select a higher range setting.

2) In 100 mT range, a gain value of +1.0 corresponds to typically 0.8%/mT (TLE4998P), or 32 LSB₁₂/mT sensitivity. It is recommended to do a final 2-point calibration of each IC within the application.

4.3 Offset Setting - OS

The offset value corresponds to an output value with zero field at the sensor. The offset value can be calculated by:

$$OUT_{OS} = OS - 16384 \quad (4.2)$$

Note: The offset value can be set outside the output range of the sensor. This feature can be used to map a magnetic range apart from 0 mT (for example -200 mT to -150 mT) to the full output range.

Table 4-3 Offset

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Offset range ¹⁾	OUT _{OS}	-16384	–	16383	LSB ₁₂	SENT/SPC
		-400		399	%DY ²⁾	PWM
Offset quantization steps	ΔOUT _{OS}	–	1	–	LSB ₁₂	–

1) Infineon pre-calibrates the samples at zero field to typically 50% output value in 100 mT range. It is recommended to do a final 2-point calibration of each IC within the application.

2) DY = PWM duty cycle

4.4 Low-Pass Filter - LP

A configurable digital low-pass filter is implemented at the output of the Hall ADC. The possible settings are shown in [Table 4-4](#). [Figure 4-1](#) shows the filter characteristics as a magnitude plot for the settings 80 Hz to 1390 Hz (from left to right). The update rate of the low-pass filter output is nominally 16 kHz.

Table 4-4 Low Pass Filter Setting

Parameter LP	Nominal cutoff frequency in Hz (-3 dB point)
0	80
1	240
2	440
3	640
4	860
5	1100
6	1390
7	Off

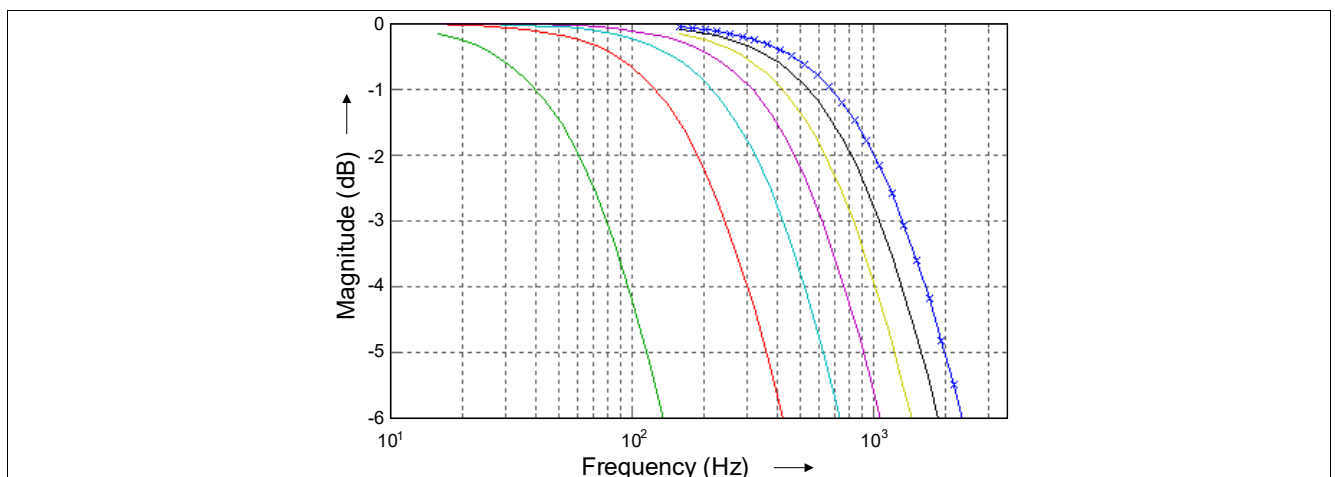


Figure 4-1 DSP Input Filter (Magnitude Plot)

Table 4-5 Low-Pass Filter

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Corner frequency variation	Δf	-20	–	+20	%	–

4.5 Clamping - CH, CL

The clamping function is useful for separating the output range into an operating range and error ranges. If the magnetic field is exceeding the selected measurement range, the output value OUT is limited to the clamping values. Any value in the error range is interpreted as an error by the sensor counterpart.

Figure 4-2 shows an example in which the magnetic field range between B_{min} and B_{max} is mapped to duty cycles between 16% and 84%.

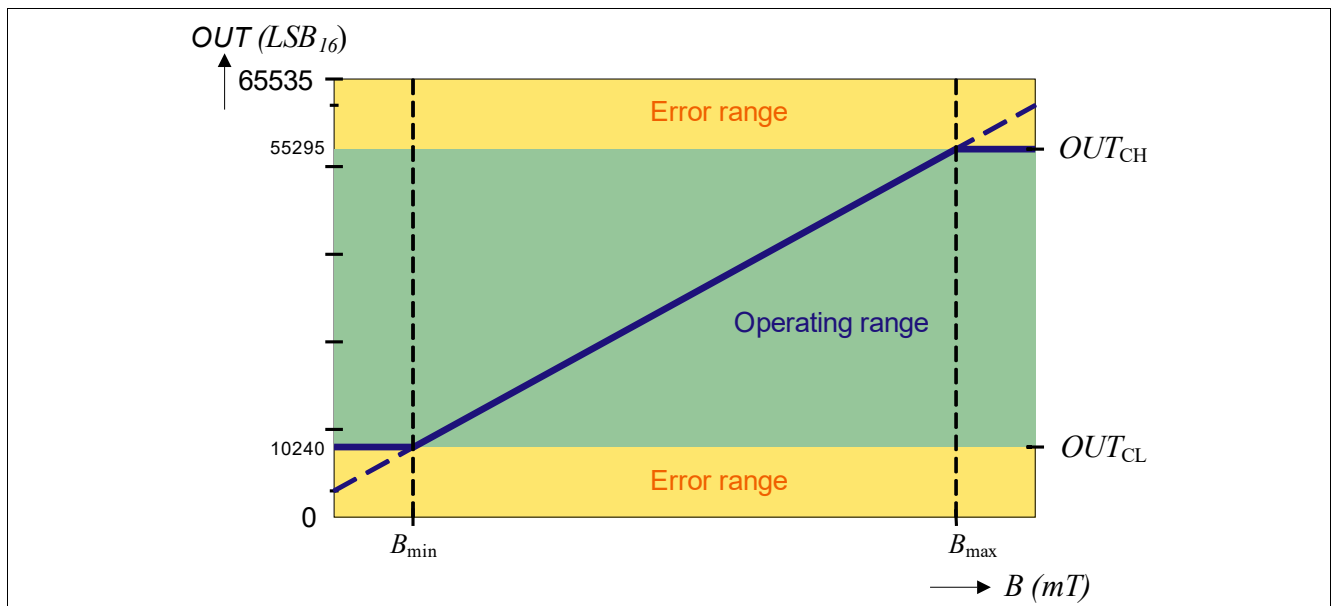


Figure 4-2 Clamping Example

Clamping - TLE4998P (all types) and TLE4998S3, S4, and S3C:

Table 4-6 Clamping

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Clamping low ¹⁾	OUT_{CL}	0	–	99.22	%DY ²⁾	PWM
		0	–	65032	LSB ₁₆	SENT
Clamping high ¹⁾³⁾	OUT_{CH}	0.78	–	100	%DY	PWM
		511	–	65535	LSB ₁₆	SENT
Clamping quantization steps ⁴⁾	ΔOUT_{Cx}	–	0.78	–	%DY	PWM
		–	512	–	LSB ₁₆	SENT

- 1) For CL = 0 and CH = 127 the clamping function is disabled.
- 2) DY = PWM duty cycle
- 3) $CY_{CLPWM} < CY_{CLPWM}$ mandatory.
- 4) Quantization starts for CL at 0%, or 0 LSB₁₂ and for CH at 100% or 4095 LSB₁₂.

The clamping values for TLE4998P (all types) and TLE4998S3, S4, and S3C are calculated by:

Clamping duty cycle low (deactivated if CL=0):

$$OUT_{CL} = CL \cdot 32 \cdot 16 \quad (4.3)$$

Clamping duty cycle high (deactivated if CH=127):

$$OUT_{CH} = (CH + 1) \cdot 32 \cdot 16 - 1 \quad (4.4)$$

Clamping - TLE4998C (all types) and TLE4998S8(D):

Table 4-7 Clamping

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Clamping value low ¹⁾	OUT _{CL}	0	–	64512	LSB ₁₆	SENT,SPC
Clamping value high ¹⁾²⁾	OUT _{CH}	1023	–	65535	LSB ₁₆	SENT,SPC
Clamping quantization steps ³⁾	ΔOUT _{Cx}	–	1024	–	LSB ₁₆	SENT,SPC

1) For CL = 0 and CH = 63 the clamping function is disabled.

2) OUT_{CL} < OUT_{CL} mandatory.

3) Quantization starts for CL at 0 LSB₁₂ and for CH at 4095 LSB₁₂.

The clamping values for TLE4998C (all types) and TLE4998S8(D) are calculated by:

Clamping duty cycle low (deactivated if CL=0):

$$OUT_{CL} = CL \cdot 64 \cdot 16 \quad (4.5)$$

Clamping duty cycle high (deactivated if CH=63):

$$OUT_{CH} = (CH + 1) \cdot 64 \cdot 16 - 1 \quad (4.6)$$

4.6 Interface Timing Setup - Prediv

The Prediv parameter has different functionalities, depending on the used TLE4998 type. All timing settings are subject to the internal RC oscillator frequency accuracy of ±20%.

Note: The implementation of the timing setup is different in the SENT types TLE4998S8(D) than in the TLE4998S3, S4, and S3C.

PWM Frequency - TLE4998P (all types)

The nominal PWM frequency of the TLE4998P is calculated by:

$$f_{PWM} = OSC_{Clk} / (\text{Prediv} + 1)$$

$$OSC_{Clk} = 1953 \text{ Hz} \pm 20\% \quad (4.7)$$

Table 4-8 Pre-divider Setting

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
PWM output frequency	f_{PWM}	122	–	1953	Hz	OSC _{clk} ...oscillator clock

SENT Unit Time - TLE4998S3, S4, and S3C

The nominal unit time of the TLE4998S3, S4, and S3C is calculated by:

$$f_{UNIT} = (\text{Prediv} \times 2 + 2) / Clk_{UNIT}$$

$$Clk_{UNIT} = 8\text{MHz} \pm 20\% \quad (4.8)$$

Table 4-9 Pre-divider Setting

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
SENT unit time	t_{UNIT}	2.0	–	4.0	μs	$Clk_{UNIT}=8\text{MHz}^1$

1) default setting Prediv = 11 for 3 μs nominal unit time. Useable range is 7 to 15.

SENT/SPC Unit Time - TLE4998C (all types) and TLE4998S8(D)

The nominal unit time of the TLE4998C and TLE4998S8(D) is calculated by:

$$f_{UNIT} = (\text{Prediv} + 16) / Clk_{UNIT}$$

$$Clk_{UNIT} = 8\text{MHz} \pm 20\% \quad (4.9)$$

Table 4-10 Pre-divider Setting

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
SENT/SPC unit time	t_{UNIT}	2.0	–	3.88	μs	$Clk_{UNIT}=8\text{MHz}^1$

1) default setting Prediv = 8 for 3 μs nominal unit time.

4.7 SENT/SPC Frame Settings - F

The parameter F is only available for the TLE4998C (all types), and the TLE4998S8(D). It controls the frame type of the SENT/SPC protocol.

Table 4-11 Frame Selection

Frame Type	Parameter F	Data Nibbles
16 bit Hall, 8 bit temperature	0	6 nibbles
16 bit Hall	1	4 nibbles
12 bit Hall, 8 bit temperature	2	5 nibbles
12 bit Hall	3	3 nibbles

4.8 SPC Trigger Mode - Prot

The parameter Prot is only available for the TLE4998C (all types). It controls the SPC trigger mode. The trigger modes are described in the TLE4998C data sheet.

Table 4-12 SPC Trigger Mode Selection

Mode	Parameter PMSB	Parameter PLSB
Synchronous	0	No effect
Dynamic range selection	1	0
ID selection	1	1

4.9 Temperature Compensation - TL, TQ & TT

The TLE4998 has an integrated third-order temperature compensation using the coefficients TL, TQ, and TT, which is used to compensate the thermal drift of the Hall cell (pre-configured by Infineon).

The magnetic field strength of a magnet depends on the temperature. This material constant is specific for the different magnet types. The temperature compensation parameters TL and TQ of the TLE4998 can be adapted to compensate this temperature dependency of the magnet in the application. The TT value is fixed and cannot be modified.

Three parameters are used for the application temperature compensation:

- Reference temperature T_0
- A linear part (1st order) TC_1
- A quadratic part (2nd order) TC_2

The detailed procedure to derive the optimum TL and TQ parameters for a given magnet characteristic is described in [Chapter 6](#).

Table 4-13 Temperature Compensation

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
1 st order coefficient TC_1	TC_1	-1000	–	2500	ppm/ °C	1)
Quantization steps of TC_1	ΔTC_1	–	15.26	–	ppm/ °C	–
2 nd order coefficient TC_2	TC_2	-4	–	4	ppm/ °C ²	2)
Quantization steps of TC_2	ΔTC_2	–	0.119	–	ppm/ °C ²	–
Reference temp.	T_0	-48	–	64	°C	–

- 1) Relative range to Infineon TC_1 temperature pre-calibration, the maximum adjustable range is limited by the register-size and depends on specific pre-calibrated TL setting, full adjustable range: -2441 to +5355 ppm/°C.
- 2) Relative range to Infineon TC_2 temperature pre-calibration, the maximum adjustable range is limited by the register-size and depends on specific pre-calibrated TQ setting, full adjustable range: -15 to +15 ppm/°C².

5 SENT/SPC Checksum Calculation

For the TLE4998S and TLE4998C, the Checksum nibble of the SENT/SPC protocol is a 4-bit CRC of the data nibbles including the status nibble. The CRC is calculated using a polynomial $x^4 + x^3 + x^2 + 1$ with a seed value of 0101.

It is implemented as a series of XOR and shift operations as shown in the following flowchart:

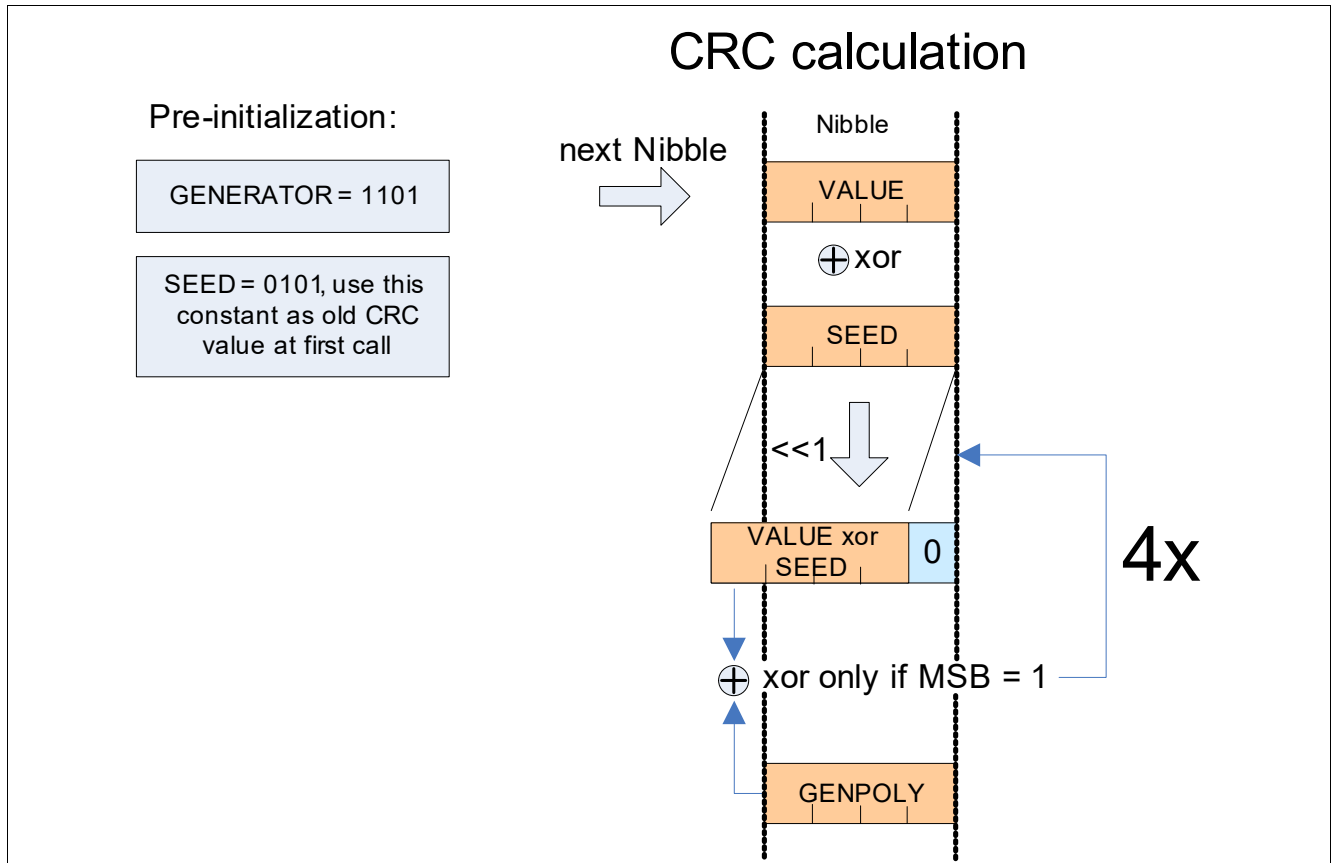


Figure 5-1 CRC Calculation

A microcontroller implementation may use an XOR command plus a small 4-bit lookup table to calculate the CRC for each nibble.

```
// Fast way for any  $\mu$ C with low memory and compute capabilities
char Data[8] = {...}; // contains the input data (status nibble, 6 data nibble, CRC)
// required variables and LUT
char CheckSum, i;
char CrcLookup[16] = {0, 13, 7, 10, 14, 3, 9, 4, 1, 12, 6, 11, 15, 2, 8, 5};
CheckSum = 5; // initialize checksum with seed "0101"
for (i=0; i<7; i++) {
    CheckSum = CheckSum ^ Data[i];
    CheckSum = CrcLookup[CheckSum];
}
; // finally check if Data[7] is equal to CheckSum
```

Figure 5-2 Example Code for CRC Generation

6 Calibration of TLE4998 Temperature Compensation

A temperature compensation mechanism is implemented in the TLE4998 to account for thermal drift of the Hall probe sensitivity and thermal reduction of the remanent magnetization of a permanent magnet used in a position sensing application. Initially, the TLE4998 is pre-configured by Infineon to have a constant magnetic sensitivity over temperature.

In case the TLE4998 is used to measure an absolute magnetic field, for example in a current sensing application, then no additional adaption of the temperature compensation by the user is required.

If the TLE4998 is used in a position sensing application where it measures the magnetic field generated by a moving permanent magnet, then it is typically desired that the output signal of the TLE4998 depend only on the magnet position. In this case, a user adaptation of the temperature compensation is required to account for thermal reduction of the magnet's remanence. Therefore, the TLE4998 has to be configured to increase its sensitivity accordingly with increasing temperature to compensate the thermal reduction of the remanence.

This temperature coefficient of the remanence depends on the chosen magnet material, so the temperature compensation of the TLE4998 has to be adapted to the permanent magnet employed in the application.

6.1 Integrated Temperature Polynomial

The integrated temperature compensation of the TLE4998 uses a third order polynomial, as shown in [Equation \(6.1\)](#).

$$S_{\text{DSP}}(\text{TCAL}) = 1 + \frac{\text{TL} - 160}{8 \cdot 8192} \cdot \left(\frac{\text{TCAL}}{16}\right) + \frac{\text{TQ} - 128}{1024 \cdot 8192} \cdot \left(\frac{\text{TCAL}}{16}\right)^2 - \frac{\text{TT}}{32768 \cdot 8192} \cdot \left(\frac{\text{TCAL}}{16}\right)^3 \quad (6.1)$$

with:

$$\text{TCAL} = 16 \cdot (T_J - 48) \quad (6.2)$$

T_J is the junction temperature in °C. The coefficients TL, TQ, and TT are the linear, quadratic and cubic temperature compensation coefficients, respectively. They are stored in the EEPROM and pre-configured by Infineon for a constant magnetic sensitivity over temperature (see [Chapter 3.4](#) for EEPROM map).

The coefficients TL and TQ can be adapted by the user to implement a compensation of the thermal reduction of a magnet's remanence. The coefficient TT is fixed to the value pre-calibrated by Infineon. It cannot be adapted.

6.2 Application Sensitivity Polynomial

In order to find the optimum TL and TQ parameters to minimized the position signal error due to the thermal reduction of the magnet's remanence, an application sensitivity polynomial has to be derived from a sensitivity measurement in the application over temperature that describes the desired sensitivity factor as a function of temperature (see [Chapter 6.3](#)). The application sensitivity polynomial is given by [Equation \(6.3\)](#).

$$S_{\text{App}}(T_J) = 1 + \text{TC}_1(T_J - T_0) + \text{TC}_2(T_J - T_0)^2 \quad (6.3)$$

T_J is the junction temperature in °C, TC_1 (in ppm/°C) and TC_2 (in ppm/°C²) are the first and second order application temperature coefficients and T_0 (in °C) is a reference temperature.

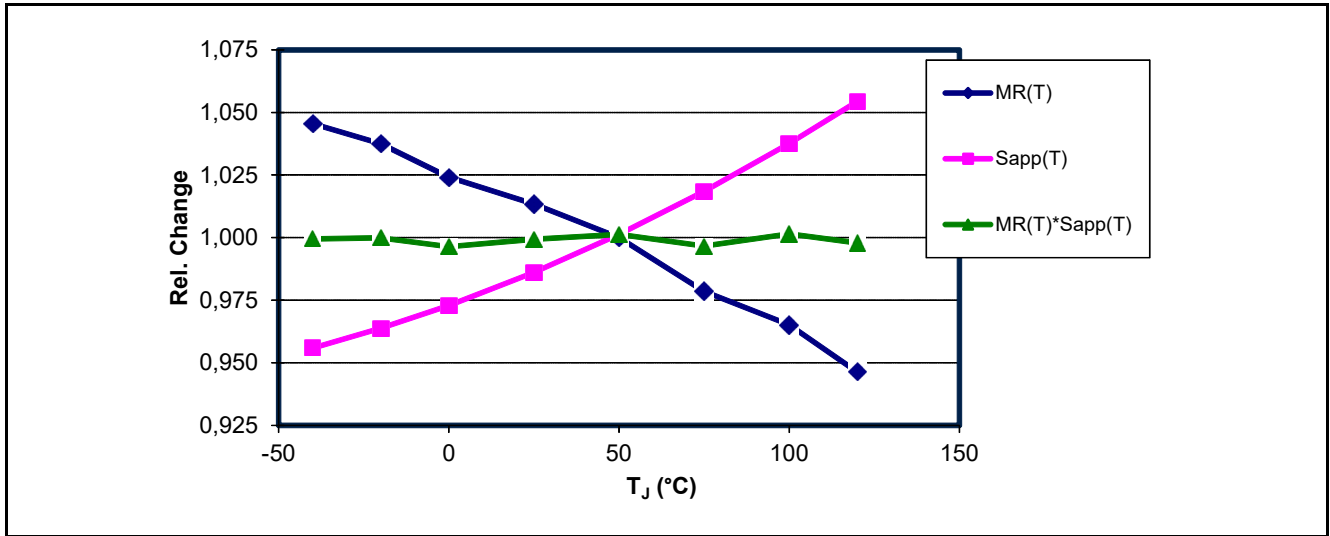


Figure 6-1 Example thermal behavior of magnetic remanence $M(T)$ and application sensitivity polynomial $S_{app}(T)$ with reference temperature 48°C .

The reference temperature T_0 is a degree of freedom that can be chosen by the user, such that the gain of the TLE4998 that is configured in the EEPROM, applies at this reference temperature.

In case the calibration of the offset and gain for the output characteristic is done after the calibration of the temperature compensation, the choice of T_0 is not relevant. In this case, the gain at a specific temperature is configured separately. A choice of $T_0 = 48^{\circ}\text{C}$ is recommended for simplicity (to match the reference temperature in the definition of TCAL in Equation (6.2)).

The application sensitivity polynomial S_{App} has to be determined in the application to approximately cancel the temperature dependency of the remanence, as stated in Equation (6.4) and illustrated in Figure 6-1.

$$S_{App}(T_J) \cdot M_R(T_A) \approx \text{constant} \quad (6.4)$$

M_R is the remanence of the permanent magnet as a function of temperature and T_A is the ambient temperature in the application that relates to the junction temperature T_J by Equation (6.5).

$$T_J = T_A + R_{th} \cdot (U \cdot I) \quad (6.5)$$

R_{th} is the thermal resistance of the TLE4998 as specified in the data sheet, U is the supply voltage and I is the supply current.

After determining the application sensitivity polynomial S_{App} from a sensitivity measurement over temperature, the sensor parameters TL_{final} and TQ_{final} for the final sensor configuration have to be adapted to combine the compensation of the Hall sensing element drift (given by the precalibrated values TL_{pre} and TQ_{pre}) and the cancellation of the thermal reduction of the magnet's remanence (given by S_{App}), as stated in Equation (6.6).

$$S_{DSPfinal}(T_J) \approx S_{DSPpre}(T_J) \cdot S_{App}(T_J) \quad (6.6)$$

$S_{DSPfinal}(T_J)$ is the integrated temperature polynomial given by the combination of Equation (6.1) and Equation (6.2), with the final parameters TL_{final} and TQ_{final} . $S_{DSPpre}(T_J)$ is the integrated temperature polynomial with the pre-configured parameters TL_{pre} and TQ_{pre} .

After determination of the application sensitivity polynomial coefficients and readout of the pre-configured TL_{pre} , TQ_{pre} , and TT parameters via the programming interface, the optimum TL_{final} and TQ_{final} parameters have to be derived from Equation (6.6) and programmed into the TLE4998.

6.3 Determination of Sensitivity Polynomial from Measurement

For the determination of the Coefficients for the application sensitivity polynomial ([Equation \(6.3\)](#)) a measurement of the temperature behavior of the sensor output in the application is recommended. A basic example for a position sensing application using the TLE4998 and a moveable permanent magnet is shown in [Figure 6-2](#).

In a setup that uses a permanent magnet, the magnetic field has a temperature dependency due to the thermal reduction of the remanence. In order to determine the optimum sensitivity compensation behavior of the sensor in to cancel this temperature dependency, the sensor's output value shall be measured at different temperatures, with the permanent magnet in a fixed position.

As the thermal reduction of the remanence depends mainly on the magnetic material used and has typically only minor variations from sample to sample, a reference measurement on a number of application samples is typically sufficient to determine a reference polynomial for the application in general, which is to be used for production. It is typically not required to perform the described measurement over temperature for every individual sample.

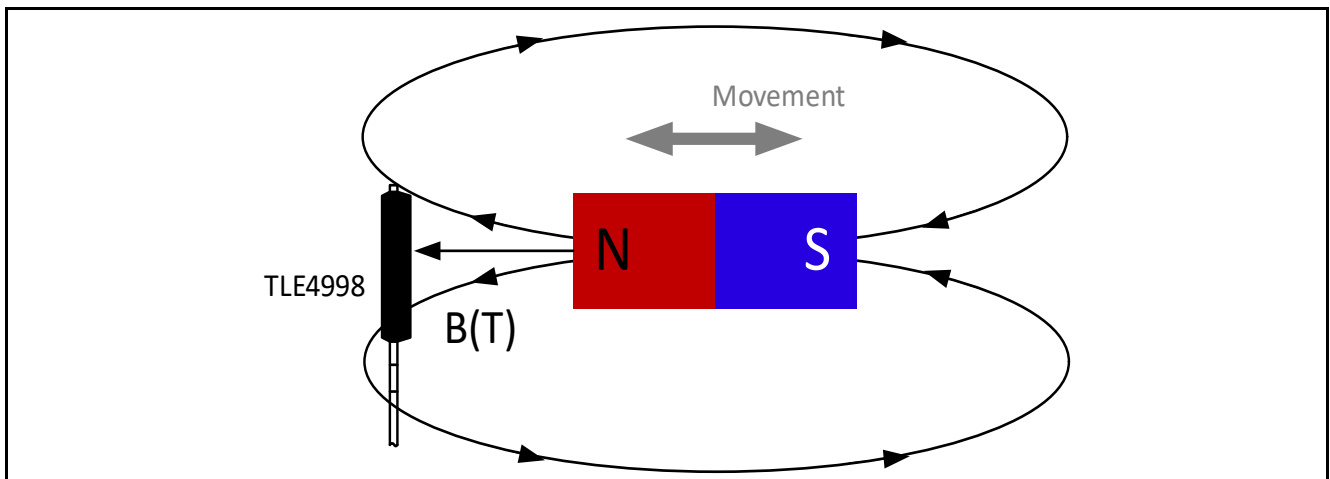


Figure 6-2 Example Position Sensing Application

With the described setup, the following procedure is used to obtain the coefficients of the application sensitivity polynomial:

- Measure the sensor output for at least three different temperatures at a defined, fixed magnet position. The magnetic flux density at the sensor shall be non-zero at this given magnet position. It is recommended for best accuracy of the calibration procedure to use a magnet position that leads to the highest possible magnetic flux at the sensor, while still being inside the configured magnetic flux range (± 50 mT, ± 100 mT, or ± 200 mT).
- For each data point, read the junction Temperature $T_J^{(i)}$, and the $DOUT^{(i)}$ value via the programming interface.
- For each data point, calculate the compensation sensitivity value $S^{(i)}$ from the $DOUT^{(i)}$ value and the output value at zero field $DOUT_0$, using [Equation \(6.7\)](#)

$$S^{(i)} = \frac{DOUT_0}{DOUT^{(i)} - DOUT_0} \quad (6.7)$$

- Plot $S^{(i)}$ as a function of $T_J^{(i)}$ and apply a quadratic fit ($cx^2 + bx + a$) which yields coefficients a, b and c (See [Figure 6-3](#)).

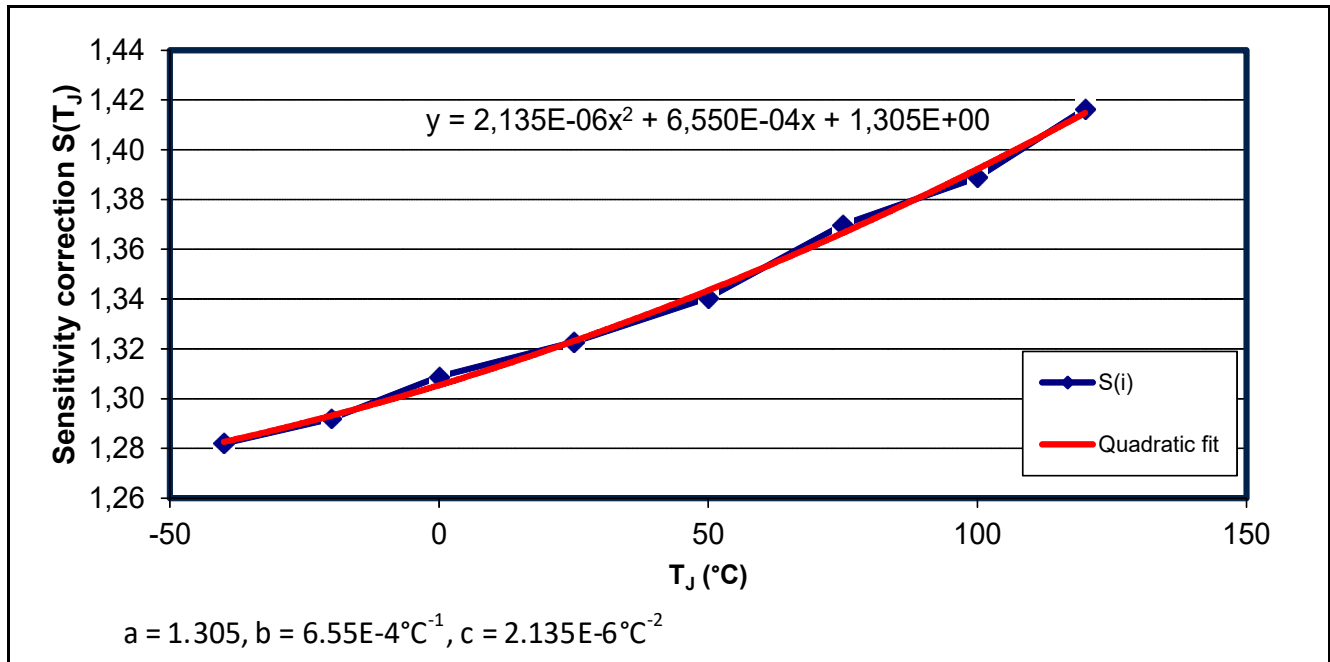


Figure 6-3 Example Polynomial Fit Procedure.

- Derive the coefficients of the application sensitivity polynomial from the parameters a, b, and c obtained from the quadratic fit using [Equation \(6.8\)](#) and [Equation \(6.9\)](#).

$$TC_1 = \frac{b + 2 \cdot c \cdot T_0}{a + b \cdot T_0 + c \cdot T_0^2} \quad (6.8)$$

$$TC_2 = \frac{c}{a + b \cdot T_0 + c \cdot T_0^2} \quad (6.9)$$

6.4 Calculation of Final Temperature Compensation Parameters

After determination of the application sensitivity polynomial S_{app} , it is necessary to adapt the temperature compensation parameters TL and TQ in the EEPROM such that the overall sensitivity of the TLE4998 shows the desired increase over temperature to compensate for the thermal reduction of the magnet's remanence in the application.

6.4.1 Algorithm for Finding the Optimum Temperature Coefficient Set

For an optimum temperature compensation in the application, the set of coefficients TL and TQ have to be found that best fulfill the condition stated in [Equation \(6.6\)](#). To find this parameter set, an error function $\varepsilon(T)$ is defined in that is minimized in an iterative procedure.

$$\varepsilon(T_J) = \frac{S_{DSPfinal}(T_J)}{C \cdot S_{DSPpre}(T_J) \cdot S_{app}(T_J)} - 1 \quad (6.10)$$

$S_{DSPfinal}(T_J)$ is the integrated temperature polynomial given by the combination of [Equation \(6.1\)](#) and [Equation \(6.2\)](#), with the final parameters TL_{final} and TQ_{final} . $S_{DSPpre}(T_J)$ is the integrated temperature polynomial with the pre-configured parameters TL_{pre} and TQ_{pre} . C is a constant to be varied in the iterative procedure.

In a second step, the error function defined in [Equation \(6.10\)](#) is summed over the temperature range in finite equidistant steps $T_J^{(i)}$. For the computation, a step size of 10°C or less is recommended. Then, the parameters TL, TQ, and the constant C are varied until the residual ϵ_{rms} in [Equation \(6.11\)](#) is minimized.

$$\epsilon_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^N (\epsilon(T_J^{(i)}))^2} \quad (6.11)$$

6.4.2 Example Implementation Code for Temperature Calibration

The following code example is done in Microsoft® Visual Basic® and can be adapted to any other programming language.

Setup of global Variables

Precalibrated parameter set read from the sensor:

- TL_pre (as stored in EEPROM)
- TQ_pre (as stored in EEPROM)
- TT (as stored in EEPROM)

Valid ranges are: TL_pre: 0...511; TQ_pre: 0...255; TT: 0...31.

Given user values in °C and ppm:

- T0 (application sensitivity polynomial reference temperature)
- TC1 (application sensitivity polynomial linear temperature coefficient)
- TC2 (application sensitivity polynomial quadratic temperature coefficient)

Valid ranges are: T0_user: -50...80, TC1_user: -0.001...0.0025, TC2_user: -0.000004...0.000004.

Last but not least we have the new setup values, we initialize partly:

- TL (used as sweep variable, needs no initialization)
- TQ (used as sweep variable, needs no initialization)

Valid ranges are: TL: 0...511; TQ: 0...255;

Sensitivity Calculation Subroutines

The first function calculates the user polynomial at a given temperature T:

```
Private Function S_app(ByVal T) As Double
    S_user = 1 + TC1 * (T - T0) + TC2 * (T - T0) ^ 2
End Function
```

The next function calculates the sensor DSP behaviour after precalibration at a given temperature T:

```
Private Function S_dsppre(ByVal T) As Double
    S_dsppre = 1 + (TL_pre - 160) * (T - 48) / 8 / 8192
                + (TQ_pre - 128) * ((T - 48) ^ 2) / 1024 / 8192
                - TT * ((T - 48) ^ 3) / 32768 / 8192
End Function
```

Finally, there is the calculation function for the DSP polynomial at a temperature T:

```
Private Function S_dsp(ByVal T) As Double
    S_dsp = 1 + (TL - 160) * (T - 48) / 8 / 8192 +
            (TQ - 128) * ((T - 48) ^ 2) / 1024 / 8192 -
            TT * ((T - 48) ^ 3) / 32768 / 8192
End Function
```

For the algorithm we need the already explained error function:

Calibration of TLE4998 Temperature Compensation

```
Private Function epsilon(ByVal T) As Double
    epsilon = -1 + S_dsp(T) / (C * S_dsppre(T) * S_app(T))
End Function
```

Iteration Loop

The iteration loop looks through all TL and TQ values and check for the smallest rms error. It is done in two steps: First it looks for a rough optimum point with a coarse step size of 10 for both parameters. In a second step it iterates again using stepsize 1 around that point to find a refined optimum.

```
Rem --> Initialize temperature sweep parameters
T_min = -40
T_max = 150
T_step = 10
n = Math.Round((T_max - T_min) / T_step)

Rem --> Initialize variables to keep track of current optimum values
epsilon_rms_opt = 9999
TL_opt = 0
TQ_opt = 0

Rem =====
Rem --> Sweep in two runs, the coarse global and the fine local search
For Rounds = 1 To 2

    Rem =====
    Rem --> Initialize sweep parameters
    Rem     First round coarse, second round fine
    If (Rounds = 1) Then
        TL_lo = 0
        TL_hi = 510
        TL_step = 10
        TQ_lo = 0
        TQ_hi = 250
        TQ_step = 10
    ElseIf (Rounds = 2) Then
        TL_lo = TL_opt - 9
        TL_hi = TL_opt + 9
        TL_step = 1
        TQ_lo = TQ_opt - 9
        TQ_hi = TQ_opt + 9
        TQ_step = 1
    End If

    Rem =====
    Rem --> TL sweep
    For TL = TL_lo To TL_hi Step TL_step

        Rem =====
        Rem --> TQ sweep
        For TQ = TQ_lo To TQ_hi Step TQ_step

            Rem =====
```

```

Rem --> Determine minimizing C by calculating average epsilon
epsilon_sum = 0
C = 1
For T = T_min To T_max Step T_step
    epsilon_sum = epsilon_sum + epsilon(T)
Next
epsilon_mean = (epsilon_sum / n)
C = epsilon_mean + 1

Rem =====
Rem --> Determine epsilon sum
epsilon_sum = 0
For T = T_min To T_max Step T_step
    epsilon_sum = epsilon_sum + epsilon(T) ^ 2
Next
epsilon_rms = Math.Sqrt(epsilon_sum / n)

Rem =====
Rem --> Determine if new optimum parameters were found
If epsilon_rms < epsilon_rms_opt Then
    epsilon_rms_opt = epsilon_rms
    TL_opt = TL
    TQ_opt = TQ
End If
Next
Next
Next

Rem =====
Rem --> Finally retrieve the best TL, TQ values stored during the sweep
TL_final = TL_opt
TQ_final = TQ_opt
After the iteration is complete, the values TLfinal and TQfinal contain the optimum values for TL and TQ. These values shall be programmed into the sensor's EEPROM.

```

6.5 Usage of Infineon's Temperature Calibration Tool

For laboratory calibration purpose, Infineon provides a simple tool to determine the calibration parameters from measurement data (see [Figure 6-4](#)).

The following sequence of steps is used for the temperature calibration the Infineon tool:

1. Measure the sensor's DOUT and TCAL registers at a fixed magnet position for different temperatures as described in [Chapter 6.3](#), enter the T_J (in °C) and DOUT (16bit) values in the table fields marked in yellow (see [Figure 6-4](#), upper left side). For the readout of this data, the Infineon TLE4998 Evaluation Kit can be used.
2. The tool automatically calculates the corresponding Sensitivity correction values S from the entered T_J and DOUT values according to [Equation \(6.7\)](#).
3. Based on the calculated S values, the tool performs a quadratic fit and calculates the Application Sensitivity Polynomial parameters TC1 and TC2 (see [Figure 6-4](#), upper right side).

Calibration of TLE4998 Temperature Compensation

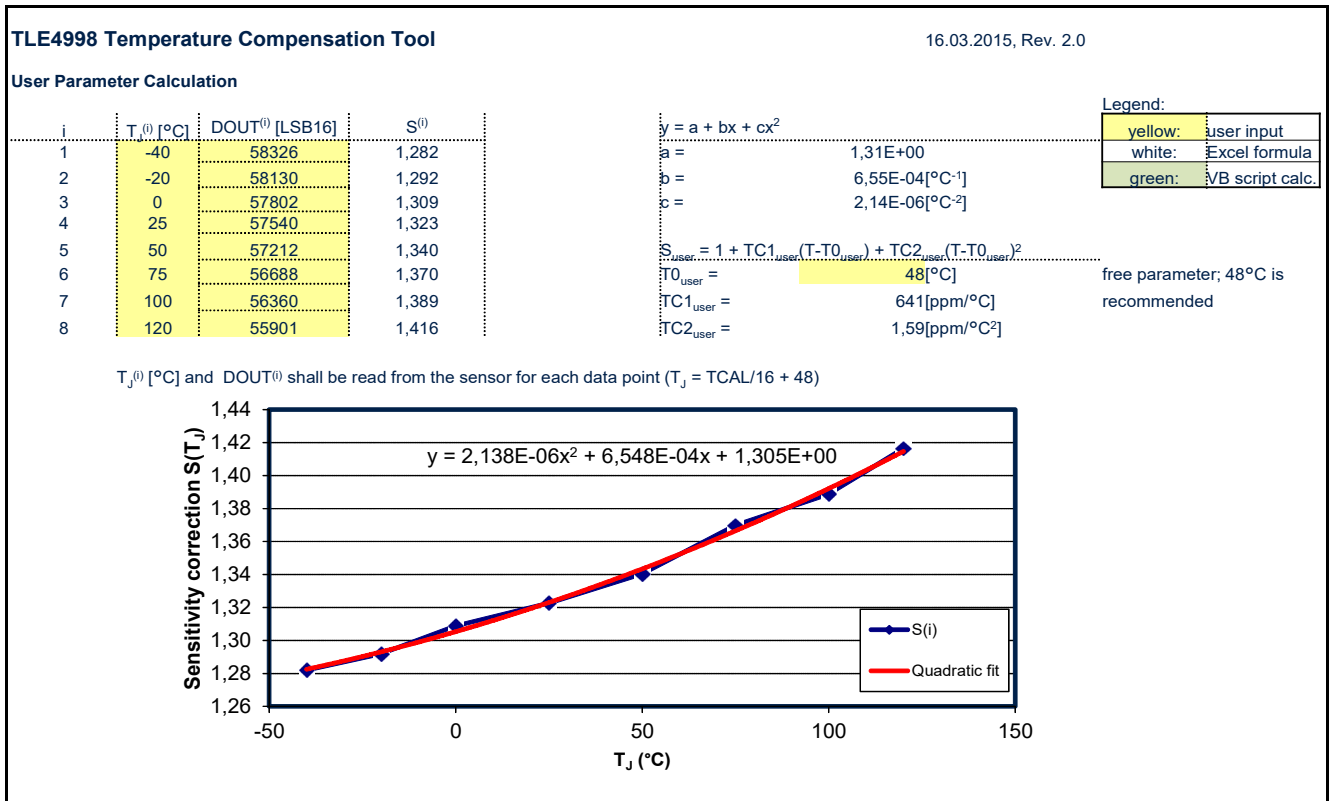


Figure 6-4 Infineon tool for temperature calibration, application sensitivity polynomial fit.

- Readout the sensor's preprogrammed TL_{pre} and TQ_{pre} values and enter them in the corresponding table fields marked in yellow (see Figure 6-5 upper left side). For the readout of this data, the Infineon TLE4998 Evaluation Kit can be used.
- The tool calculates the TL_{final} and TQ_{final} parameters out of the entered TL_{pre} and TQ_{pre} values, the (fixed) TT value and the TC1 and TC2 coefficients determined in steps 1-3. For that, an automated script is used that implements the procedure explained in Chapter 6.4. The calculated values TL_{final} and TQ_{final} appear in the corresponding table fields marked in green (see Figure 6-5 upper right side)
- Program the calculated TL_{final} and TQ_{final} values into the TLE4998 using the Infineon TLE4998 Evaluation Kit or a suitable programmer tool.

For illustration purpose, the tool also displays graphs for the preprogrammed and final sensitivity polynomials, S_{DSP,pre} and S_{DSP,final}, the application sensitivity polynomial S_{app} and the product S_{DSP,pre} * S_{app}. Ideally, after successful calibration, S_{DSP,final} should be approximately equal S_{DSP,pre} * S_{app} (compare Equation (6.6)).

The tool displays also the error that occurs due to imperfect matching of S_{DSP,final} and S_{DSP,pre} * S_{app}. Typically, after the calibration procedure, this error should be on the order of ±0.1%.

Calibration of TLE4998 Temperature Compensation

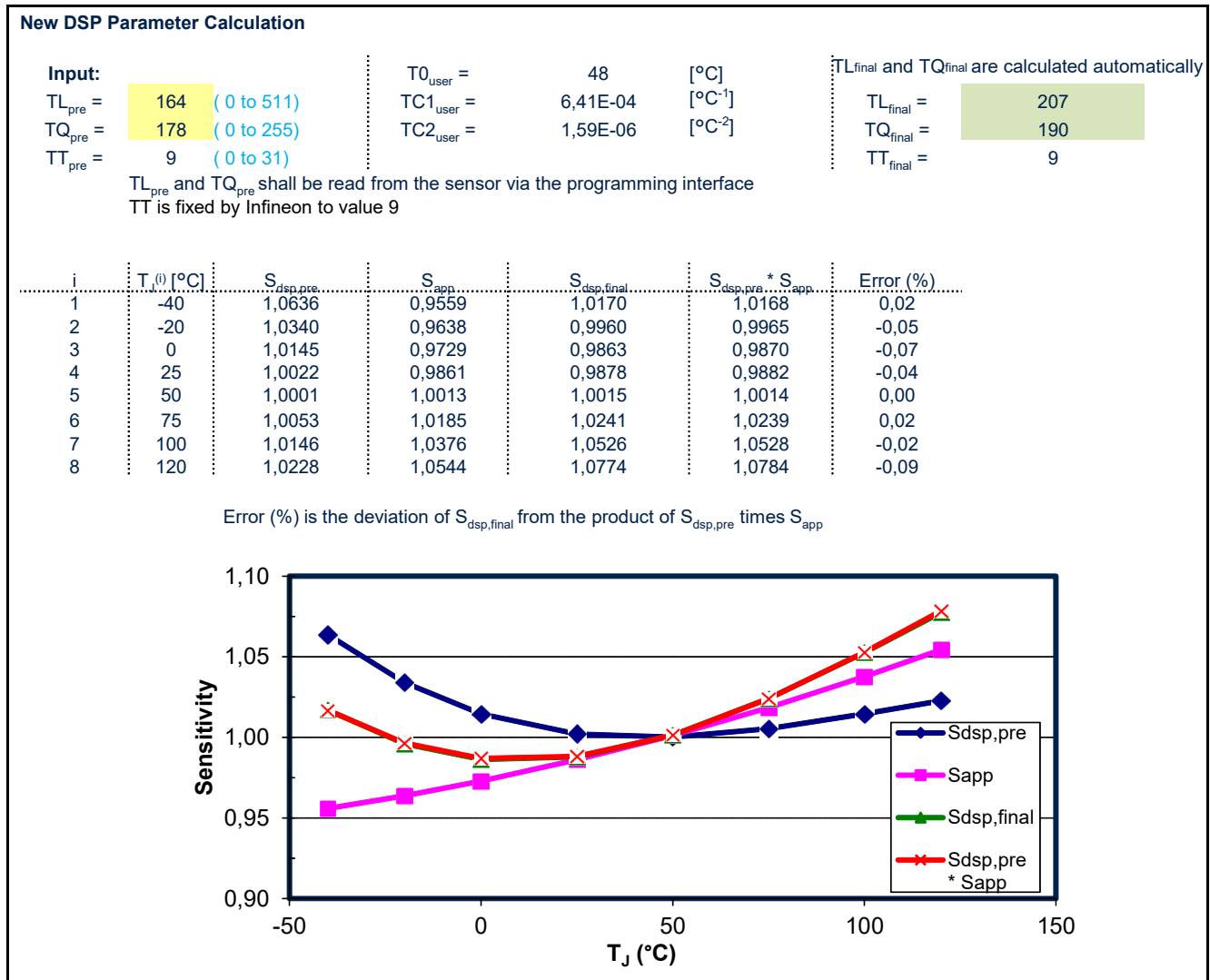


Figure 6-5 Infineon tool for temperature calibration, TL and TQ calculation.

7 Calibration of TLE4998 Output Characteristic

In a position sensing application, the maximum and minimum magnetic field sensed by the TLE4998 depends on the employed permanent magnet and the movement range covered by the application. To achieve the maximum possible accuracy in such applications, it is recommended to adapt the output characteristic of the TLE4998 to the application so the possible digital output range is matched to the magnetic input range that is available in the application.

7.1 Two-Point Calibration Procedure

Position sensor modules are typically subject to production variations in terms of magnet strength and magnet position, therefore it is recommended to do a two-point calibration of the TLE4998 after assembly of each module to achieve the desired output characteristics independent of such production variations.

In order to configure an application specific output-characteristic, a two-point calibration procedure is used, where the IC-internal representation HCAL (compare [Figure 2-1](#)) of the Hall measurement value is evaluated at two defined positions and the output offset and gain are adjusted accordingly. This procedure is illustrated in [Figure 7-1](#).

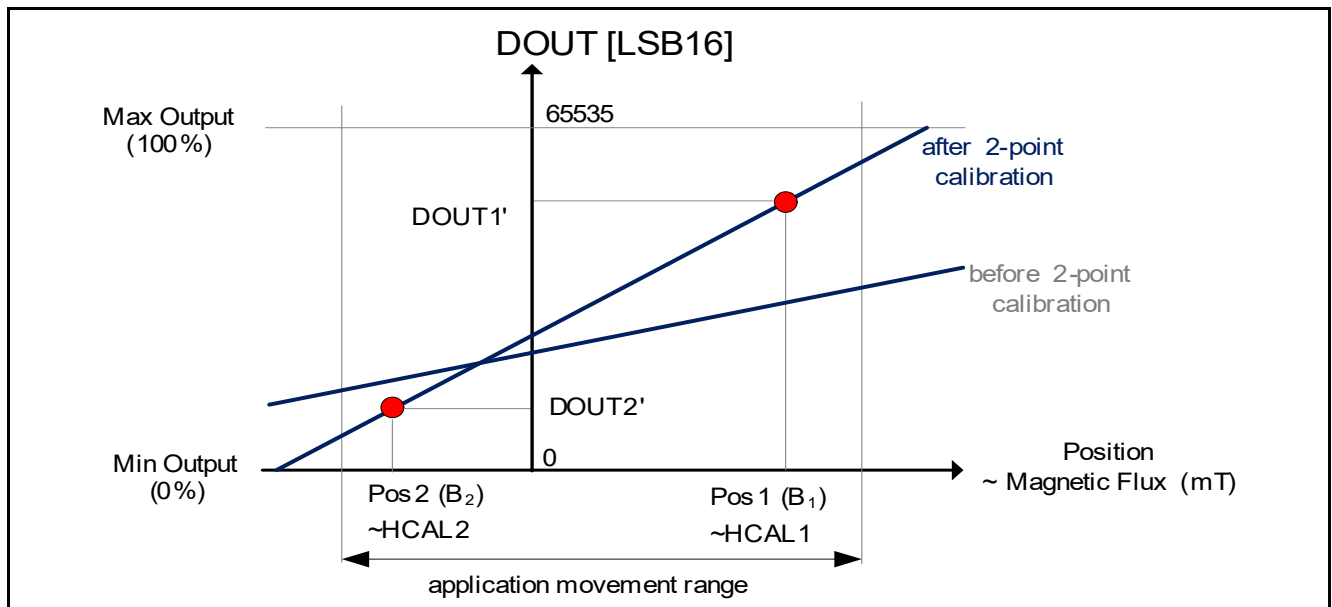


Figure 7-1 Schematic of Two-Point Calibration

The 16bit value DOUT, which is transferred on the output protocol is calculated in the TLE4998 with the configured offset (OS) and gain (G) value according to [Equation \(7.1\)](#).

$$DOUT_{16bit} = \frac{2 \cdot (G - 16384) \cdot HCAL}{4096} + 16 \cdot (OS - 16384) \quad (7.1)$$

For the two-point calibration, the following procedure is used:

1. Select two reference positions Pos1 and Pos2 for the moveable magnet in the application module. For maximum accuracy of the calibration routine it is recommended that the desired signal difference between these positions is at least half the full signal range.
2. Choose the desired output signals DOUT1' and DOUT2' which should correspond to positions Pos1 and Pos2 in the final configuration.
3. Fix the application module in position Pos1 and read the HCAL register via the programming interface. This value is HCAL1.

- Fix the application module in position Pos2 and read the HCAL register via the programming interface. This value is HCAL2.
- Calculate the according gain and offset parameters from the recorded HCAL1 and HCAL2 values and the desired DOUT1' and DOUT2' values using [Equation \(7.2\)](#) and [Equation \(7.3\)](#).

$$G = 16384 + 2048 \cdot \frac{DOUT2' - DOUT1'}{HCAL2 - HCAL1} \quad (7.2)$$

$$OS = 16384 + \frac{DOUT1' - ((G - 16384) \cdot HCAL1) / 2048}{16} \quad (7.3)$$

- Programm the gain (G) and offset (OS) values into the sensor's EEPROM.

Attention: HCAL is a 16bit signed integer value ranging from -32768 to 32767. DOUT is a 16bit unsigned integer value ranging from 0 to 65535.

7.2 Two-Point Calibration Examples

7.2.1 Calibration with Application Readout

Optimum accuracy of the TLE4998 can be achieved by using a two-point calibration with readout of the HCAL registers in the application. The sensor's output register HCAL is measured at the end points of the applications range of motion and derive the optimum offset and gain parameters from the desired DOUT values. The registers can be read using the TLE4998 Evaluation Kit.

Example

An example application has a linear movement range from x_1 to x_2 . In both positions, the register value HCAL is recorded.

In the application, it is desired to have the output value $DOUT1' = 3277 \text{ LSB}_{16}$ (5% of full 16bit range) at position x_1 and $DOUT2' = 62258 \text{ LSB}_{16}$ (95% of full 16bit range) at position x_2 .

The measured HCAL and desired DOUT' values are shown in [Table 7-1](#).

Table 7-1 Example DOUT and HCAL values for 2-point calibration

Position	measured HCAL (Hex)	HCAL (Dec, signed) Range -32768 to 32767	desired DOUT' (Hex)	DOUT' (Dec) Range 0 to 65535
x_1	EAC5 _H	-5435	0CCD _H	3277
x_2	183B _H	6203	F332 _H	62258

Applying the HCAL and DOUT' values from [Table 7-1](#) in [Equation \(7.2\)](#) and [Equation \(7.3\)](#) yields:

$$G = 16384 + 2048 \cdot (62258 - 3277) / (6203 - (-5435)) = 26763$$

$$OS = 16384 + (3277 - ((26763 - 16384) \cdot (-5435)) / 2048) / 16 = 18310$$

This corresponds to a multiplicative gain of 2.53 and an offset of 47% ($= 1926 \text{ LSB}_{12} = 30816 \text{ LSB}_{16}$), according to the formulas in [Chapter 4](#).

Attention: If the measured HCAL values are close to the range limits -32768 or 32767, saturation takes place. In this case, it is recommended to switch to a higher magnetic range (± 100 or $\pm 200 \text{ mT}$) prior to the calibration.

7.2.2 Calibration without Application Readout

In case a readout of the sensor before calibration is not desired, the sensor can be roughly calibrated just from a knowledge of the minimum and maximum magnetic flux values that occur in the application. In this case, the calibration cannot compensate any variation of parameters due to production spread of sensor IC or application module. The offset and gain are calculated only based on the minimum and maximum magnetic field in the application.

Example

An example application has a minimum magnetic flux of $B_{\min} = -25$ mT and a maximum magnetic flux of $B_{\max} = 75$ mT, over the entire range of motion at room temperature. In the application module, these magnetic flux values shall be mapped to 10% and 90% of the full output range (full 100% duty cycle for PWM versions or full 12bit or 16bit digital output for SENT and SPC versions).

The pre-calibrated gain value is 1.62 and the pre-calibrated offset value (= output at 0 mT magnetic flux) is 50%. For the optimum configuration of the sensor for this application, the range is set to ± 100 mT (± 50 mT is not suitable in this case, as B_{\max} is outside this range).

The sensitivity needs to be set in a way that the magnetic flux change from B_{\min} to B_{\max} results in an output value change of $90\% - 10\% = 80\%$. The required sensitivity is

$$(\text{OUT2} - \text{OUT1}) / (B_{\max} - B_{\min}) = 80\% / 100 \text{ mT} = 0.8 \text{ \%/mT}$$

The default sensitivity corresponding to the gain setting of 1.62 is 1.2 %/mT. To reach the desired sensitivity, the gain needs to be lowered by a factor of $0.8/1.2 = 0.667$. So the new gain setting to be programmed into the sensor is $1.62 * 0.667 = 1.08$.

The offset needs to be adapted accordingly, so the center value of the magnetic range corresponds to 50% of the full output. In this example, the center of the magnetic range is:

$$B_{\text{center}} = (B_{\max} - B_{\min}) / 2 = 75\text{mT} - (-25 \text{ mT}) / 2 = 25 \text{ mT}$$

To find the optimum offset setting, the desired magnetic flux value B_{center} which should correspond to 50% output is multiplied by the gain and the resulting value is subtracted from 50%.

Thus, for this example the offset setting to be programmed in the sensor is: $50\% - (25\text{mT} * 0.8 \text{ \%/mT}) = 30\%$

Revision History

Page or Item	Subjects (major changes since previous revision)
Rev 1.3, 2018-02	
Page 12	Added hardware version ID and hardware status content for TLE4998C8(D) B2 design
Page 14	Updated Flowchart description to include hardware status content for TLE4998C8(D) B2 design
Rev 1.4, 2020-10	
Page 26	Update of equation 6.1

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