TLE4997

Configuration and Calibration of Linear Hall Sensor

User's Manual

v01_01, 2019-08

Sense & Control

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Table of Contents

1 Scope

This document is valid for all TLE4997 variants and derivates. It gives a detailed description of the configuration and calibration procedure, which is recommended to configure the TLE4997 for optimum accuracy in a sensing application.

2 TLE4997 Signal Processing

The TLE4997 uses a fully 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 and the temperature data acquired by an integrated temperature 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 of Gain and Offset.
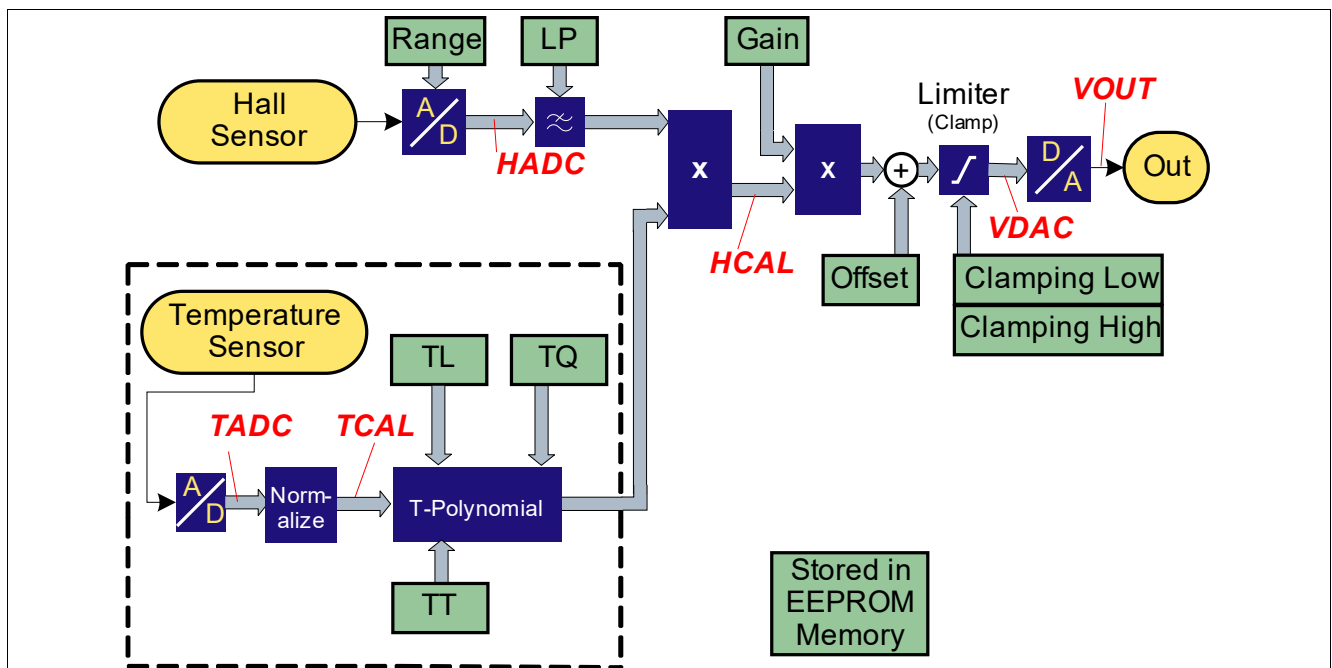
Figure 2-1 Signal Flow Diagram of the TLE4997

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 and stored in the HCAL register. The first order (TL) and second order (TQ) coefficients of the polynomial are configurable. The third order coefficient (TT) is fixed.
4. The HCAL value is multiplied by the configured gain value.
5. The configured offset value is added to the HCAL value.
6. The digital Hall value is clamped according to the configured upper and lower clamping limits. The output value of the clamping stage is converted from digital to analog.
7. An output voltage is transmitted on the OUT pin and is proportional to the supply voltage (ratiometric DAC).

3 TLE4997 Programming

3.1 Programmer Connection

Figure 3-1 shows the connection of the TLE4997 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 TLE4997 type for pinout).
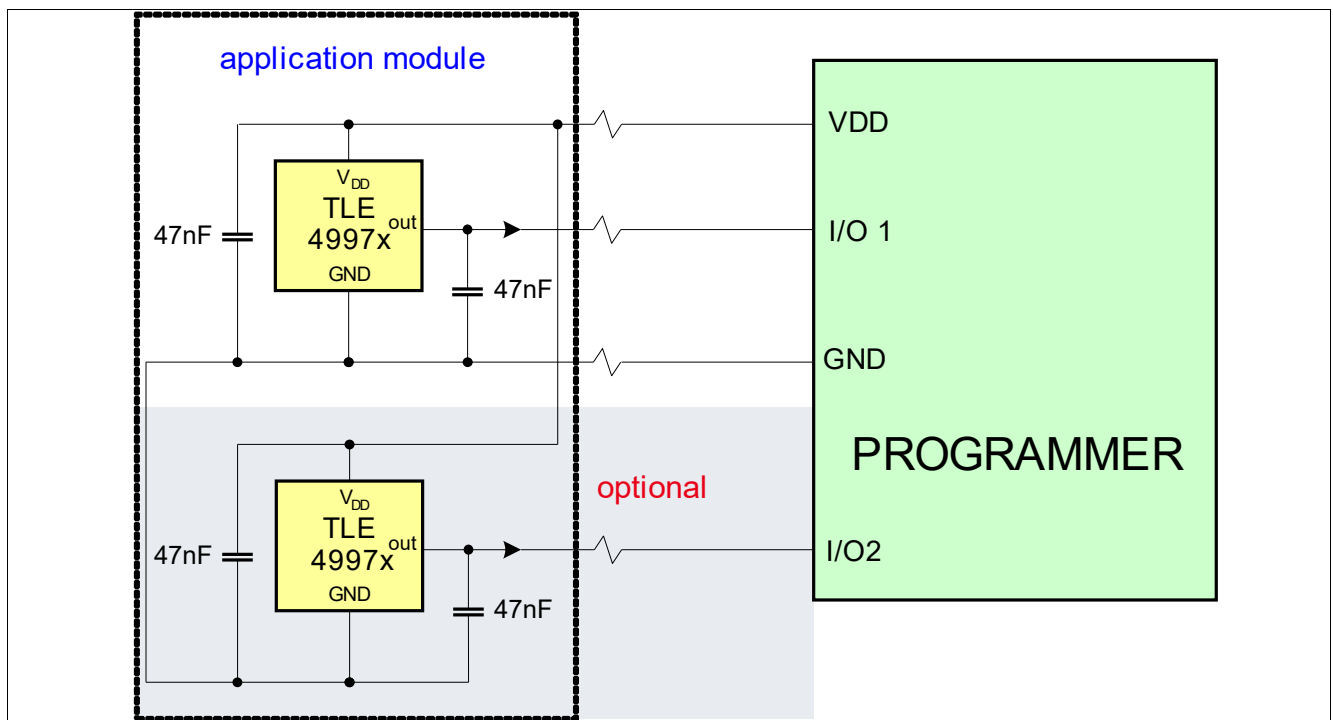
Figure 3-1   Connection of TLE4997 to Programmer

Table 3-1   Pin Functions for Programming Interface

Pin	Programming Function
VDD	Programming interface clock
GND	Ground
OUT	Programming interface data I/O

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.
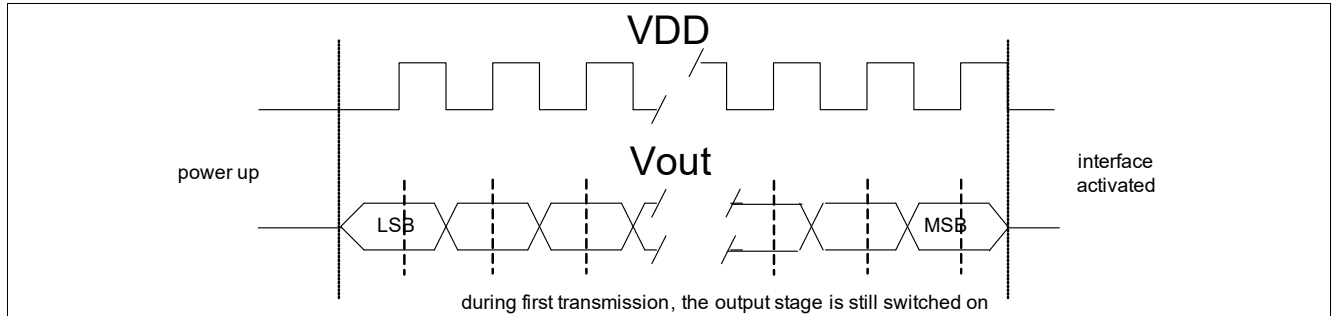
Figure 3-2   First Frame Transmission to the Sensor

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**.
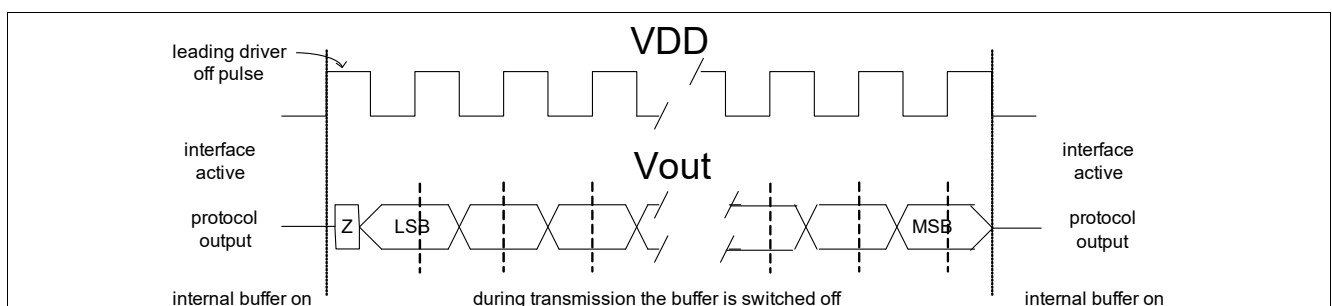
Figure 3-3   Further Frame Transmisson from the Programmer to the Sensor (Write Access)

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 3.3.2**.
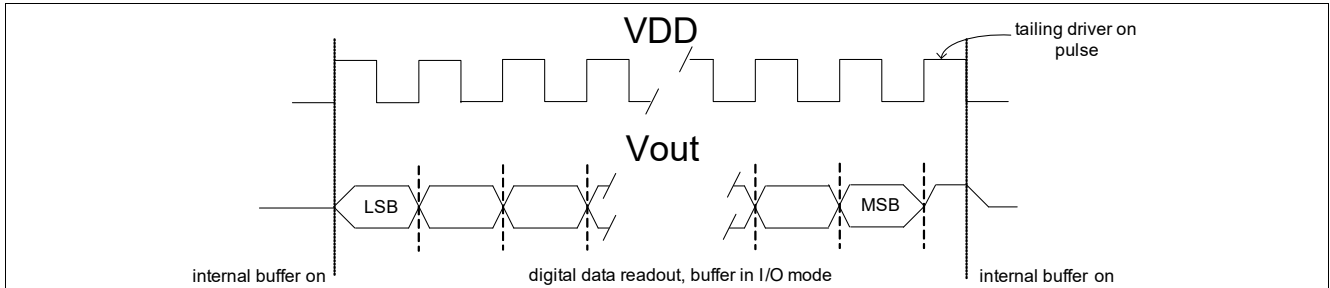
Figure 3-4   Frame Transmisson from the Sensor to the Programmer (Read Access)

3.3   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 follwing way (bit 0 is the LSB, bit 20 is the MSB):

bit0 XOR bit2 XOR bit4 XOR …. XOR bit20 = 0

bit1 XOR bit3 XOR bit5 XOR …. XOR bit19 = 0
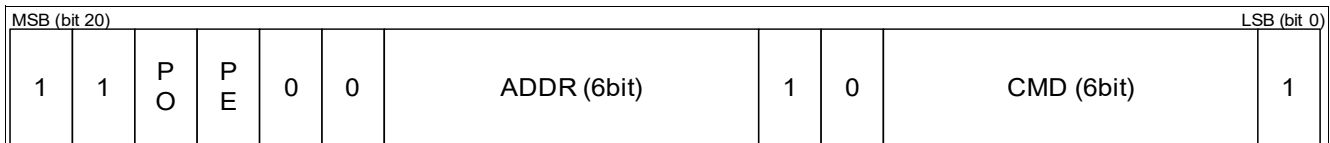
Figure 3-5   Command Frame Structure

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)
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)
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

3.3.1 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):

bit0 XOR bit2 XOR bit4 XOR …. XOR bit20 = 0

bit1 XOR bit3 XOR bit5 XOR …. XOR bit19 = 0

MSB (bit 20)					LSB (bit 0)
1	0	P O	P E	DATA (16bit)	1
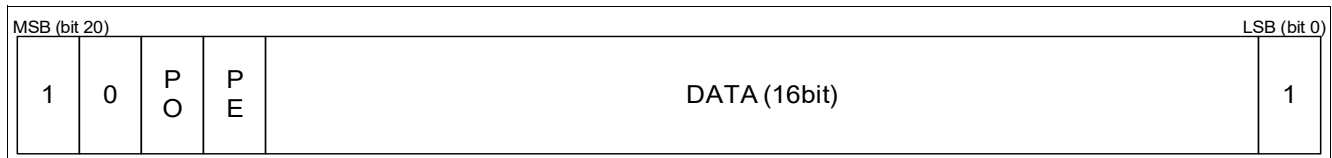
Figure 3-6   Data Frame to Sensor

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 is to check the plausibility of the received data.

MSB (bit 20)			LSB (bit 0)
1	ADR (3 LSBs)	DATA (16bit)	1
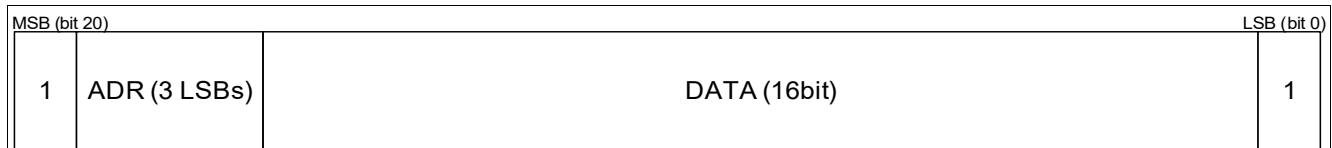
Figure 3-7   Data Frame from Sensor

3.3.2 Interface Specification

Table 3-3 specifies the operating conditions of the programming interface, which must be met in order to ensure correct operation of the TLE4997 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	$0.0^{1)}$	–	210	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

1) >47nF soldered to the device required in case that connectivity failures can influence the programming voltage.

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**.
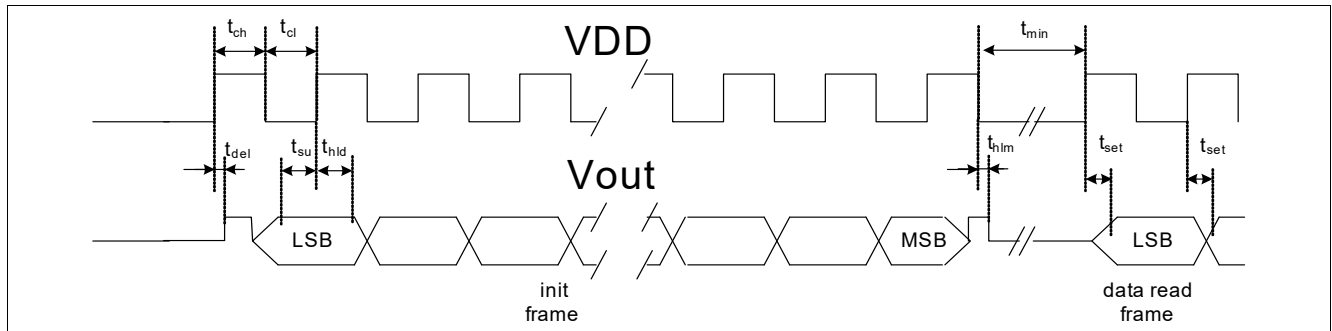
Figure 3-8   Frame Timing

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	$V_{DD,CLKHI}$	8.8	9.4	10	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_{DD} - 2	–	$V_{DD,CLKHI}$	V	OUT follows V_{DD} if 'high'
OUT data out low level	$V_{O,OLOW}$	0	–	2.0	V	
OUT data in high level	$V_{O,IHIGH}$	3.0	V_{DD}	V_{DD} + 0.1	V	
OUT data in low level	$V_{O,ILOW}$	-0.2	0.0	0.1	V	
OUT data input current	I_O	-50	–	50	mA	[1]
V_{DD} clock high time	t_{CH}	2.4	50	100	µs	5k...250kBit/s
V_{DD} clock low time	t_{CL}	1.6	4.0	100	µs	5k...250kBit/s
Data in setup time	t_{SU}	1.5	2.0	–	µs	to rising V_{DD}
Data in hold time	t_{HLD}	2.3	3.0	–	µs	after rising V_{DD}
Data out settling time	t_{SET}	–	1.0	1.7	µs	after rising V_{DD}
Time between frames	t_{MIN}	10.0	–	–	µs	
Buffer off delay	t_{DEL}	10.0	25.0	–	µs	[2]
Buffer on delay	t_{HLM}	–	5.0	10.0	µs	[2][3]

1) capacity of external driver, especially during initial interface access (to overwrite ratiometric device output).

2) to reduce collisions with the ext. driver, it must be switched on slower than t_{DEL} min. and switched off faster than $t_{HLM\ max.}$; charge/discharge behaviour on V_{OUT} depends also on capacitive output load.

3) to reach again a valid and stable ratiometric V_{OUT} signal state, please check the power-on time in the data sheet.

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.
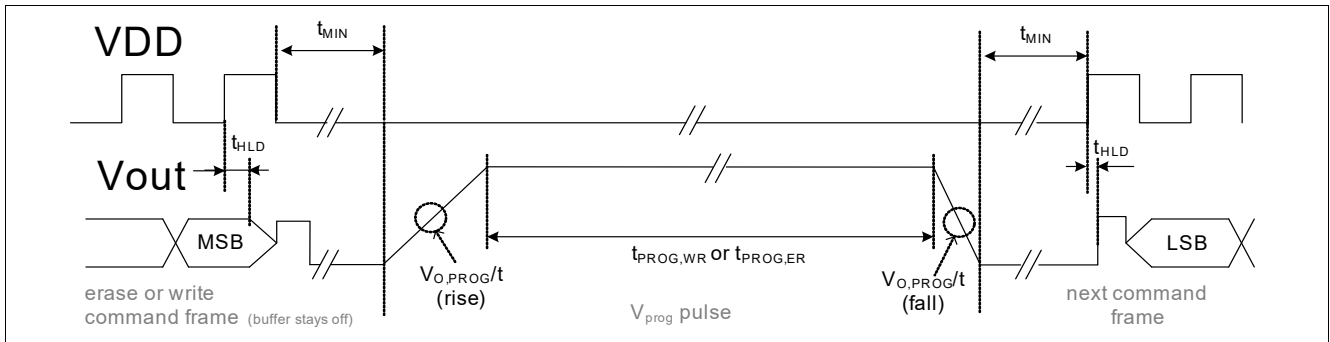
Figure 3-9   Programming Pulse Timing

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.
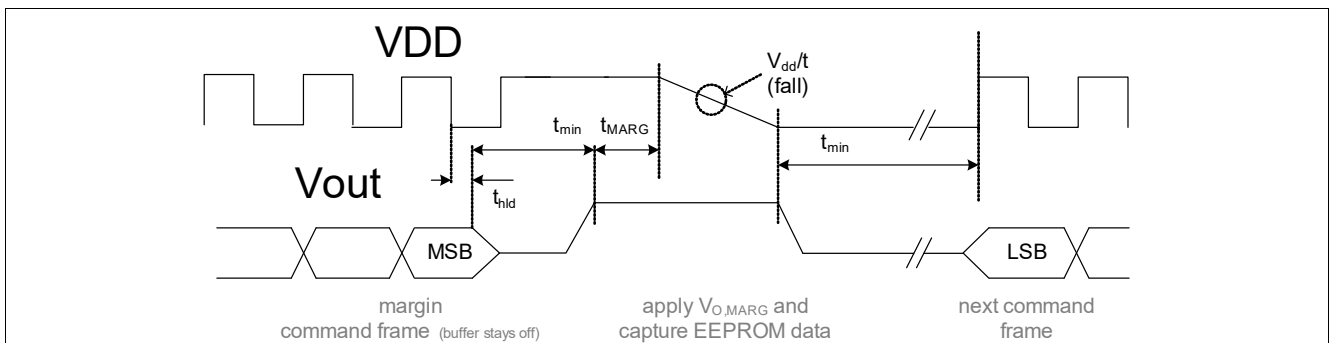
Figure 3-10 Margin Check Timing

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	–	20	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	V	check "1"
				0.4	V	check "0"
Margin setup time	t_{MARG}	200	–	–	µs	
V_{DD} slope for margin	V_{DD}/t	5	10	150	V/µs	
OUT program level	$V_{O,PROG}$	19.2	19.3	19.4	V	

Table 3-5   Electrical and Timing Specification of the Programming Pulse and Margin Voltage (cont'd)

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
OUT program slope (rise)[1]	$V_{O,PROG}/t$	–	–	2	V/µs	time to reach $V_{O,PROG}$ shall not exceed 50 µs
OUT program slope (fall)[1]	$V_{O,PROG}/t$	-10	–	–	V/µs	time to reach 1v max. shall not exceed 50 µs
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.

3.4   Register Map

Table 3-6 shows the internal registers of the TLE4997 (compare also **Figure 2-1**).

Table 3-6   TLE4997 Register Map

Address	Symbol	Function	R/W
05_H	HCAL	Calibrated Hall value	read only
06_H	TCAL	Calibrated temperature value, including reference temperature T_0	read only
07_H	VDAC	Calculated DAC value, incl. clampling	read only
$0A_H$	HADC	Uncalibrated Hall ADC value	read only
$0B_H$	TADC	Uncalibrated temperature ADC value	read only
$0F_H$	STATUS	Status register	read only
$10_H...19_H$	EEPROM	EEPROM registers (see **Chapter 3.5**)	read/write
20_H	DAC_SET	Direct setup of DAC value	read/write
21_H	TEST	Test mode register	read/write

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

HCAL

This register contains the temperature 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: $T_J = (TCAL/16+48)$ [°C].

VDAC

This register contains a 12 bit unsigned decimal result applied to the internal DAC for the ratiometric output stage. The value range is from 0 to 4095 and corresponds to 0% to 100% of V_{DD}.

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.

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 must be '0' as long as the lockbits are not programmed. After setting the lockbits the lock can be verified by refreshing the EEPROM content and checking this bit before the supply of the device is removed or the interface is closed.
- 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 must be "0", otherwise more than one EEPROM address has a parity error.
- perr_col must be "0", otherwise one or more EEPROM columns have a parity error.
- HWver contains the actual silicon revision starting with 0 (="000"). The latest version from 8' manufacturing line is version 3 (="011", availability from mid 2006 and released for productive use).
- ROMSIG has to be 1F$_H$, otherwise the DSP ROM is not valid and the device is defective.

DAC_SET

This register contains a 12 bit unsigned decimal value. When the DAC test bit is set, the value of this register is used on the ratiometric output.

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 (MSB)	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0 (LSB)
0	DAC test	0	0	DSP stop	DSP off	REF off	0	0	FEC off	0	0	0	0	0	0

Figure 3-12 Test 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 accessing 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.
- "DAC test" switches from the DSP DAC value to the DAC_SET value. This allows setting any DAC value directly to measure the output voltage for a given DAC value for calibration proposes.

3.5 EEPROM Map

Figure 3-13 shows the content of the EEPROM registers.

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_I	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, USER, clamping low	P_I	LH	USER		CL - Clamping low (bit 11...0)											
12_H	Clamping high value	P_I	Reserved			CH - Clamping high (bit 11...0)											
13_H	Gain	P_I	G - Gain (bit 14...0)														
14_H	Offset	P_I	OS - Offset (bit 14...0)														
15_H	TQ value, TT value	P_I	TQ - quadratic temperature coefficient (bit 7...0)							precal area - do not modify TT - register (bit 6 ... 0)							
16_H	LP value, Range, TL Value, IC lock low	P_I	LP - low pass (bit 0,2,1)		R-Range (bit 1,0)	TL - linear temperature coefficient (bit 8...0)											LL
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														

Figure 3-13 EEPROM Map of TLE4997 (all types).

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 purple fields are used to determine the condition of the parameters by an external programming software (user defined) and 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_I for all odd columns (bit1, bit3, ... bit15=MSB) is odd. The parity P_I of every EEPROM line (address 0x10 ... 0x19) needs to be calculated so that the sum of its bits is always odd.

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

User Bits

The two USER bits are free bits which can be used by the system integrator, for example to track calibration steps.

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.

3.6 Programming Flow

The programming flow diagram in **Figure 3-14** 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 = $F93D_H$ or $FB3D_H$, compare **Chapter 3.4**), 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 3.3.2**).
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 3.3.2**).
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 3.3.2**).
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.

EEPROM programming

$V_{dd} = 5V$

INIT-CMD:
cmd=0x01
adr=0x0F
READ DATA

Is 0xF93D or 0xFB3D ? — NO — ILLEGAL STATUS: analyse problem

CMD (write):
cmd=0x09
adr=0x21
DAT: 0x0640
(DSP, FEC, REF off)

CMD (b read)
cmd=0x03
adc=0x10
RD. B-DATA
CMD (read)
cmd=0x01
adc=0x18
READ DATA
CMD (read)
cmd=0x01
adc=0x19
READ DATA

10x 16bit → **> EEP_OLD <** Store this initial dataset (allows later restore)

User input, TC setup algorithm or 2P calibration algorithm setup

Create erase pattern for programming ← EEP_OLD / EEP_NEW — 2x 10x 16bit ← **> EEP_NEW <** Given by TC setup and/or 2P algorithms etc.

For each line I from 0x10 to 0x19:
EEP_PROG[I] = INVERT ((EEP_OLD[i] XOR EEP_NEW[i] AND EEP_OLD[i])
(as precal areas must not be changed, the bits in this areas must remain '1')

EEP_PROG

CMD (bwrite)
cmd=0x0b
adc=0x10
WR. B-DATA
CMD (write)
cmd=0x09
adc=0x18
WR. DATA
CMD (write)
cmd=0x09
adc=0x19
WR. DATA

CMD (erase):
cmd=0x0D
adr=0x00
V_{prog} PULSE

2x 10x 16bit

Create write pattern for programming ← EEP_OLD / EEP_NEW

For each line I from 0x10 to 0x19:
EEP_PROG[I] = (EEP_OLD[i] XOR EEP_NEW[i]) AND EEP_NEW[i]
(as precal areas must not be changed, the bits in this areas must remain '0')

EEP_PROG

CMD (write):
cmd=0x0C
adr=0x00
V_{prog} PULSE

CMD(marg.):
cmd=0x0E
adr=0x00
V_{marg}+V_{dd} ramp

Readout could be looped for several margin voltages (starting from a very high voltage e.g. 5V) to find the margin level of the EEPROM

see above (like complete readout procedure for EEP_OLD)

CMDs (read)
cmd=0x03/01
adr=0x10/8/9
READ DATA

content = EEP_NEW ? — NO — margin higher required limit ? — NO — ILLEGAL MARGIN READ: analyse problem

Optionally do a last status readout (adr. 0x0F) to check the IF mode is still active and the device is ok.
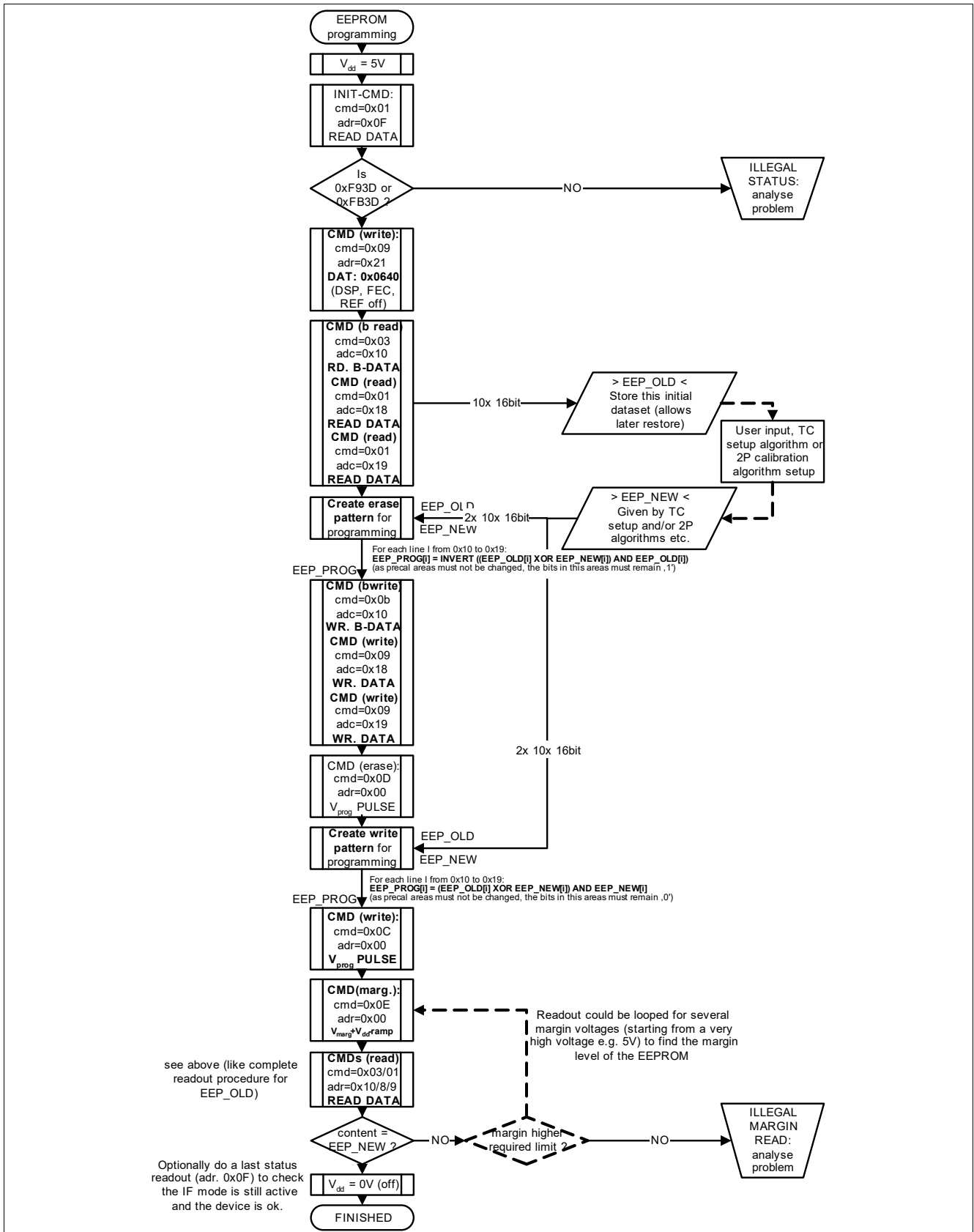
$V_{dd} = 0V$ (off)

FINISHED

Figure 3-14 Programming Flow

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

3.6.1 Setting the TEST register

The following steps are used to set the TEST register:

1. Send a write command (TEST register set: Command 09_H, Adress: 21_H).
2. Send a new data word for the register.

3.6.2 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.

3.6.3 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

3.6.4 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] = INVERT ((EEP_OLD[i] XOR EEP_NEW[i]) AND EEP_OLD[i])

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

Table 3-7   Erase Array Example

EEP_OLD	0101010**1**01010101
EEP_NEW	0101110**0**01010101
EEP_PROG	1111111**0**11111111

3.6.5 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] XOR EEP_NEW[i]) AND EEP_NEW[i]

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

Table 3-8   Write Array Example

EEP_OLD	0101**0**10101010101
EEP_NEW	0101**1**10001010101
EEP_PROG	0000**1**00000000000

3.6.6 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 $V_{O,MARG}$.

3.6.7 DATA access example

Following steps are required to readout other internal data like the calibrated temperature and Hall value (as shown below in **Table 3-15**). This routines can also be used for an EEPROM access (in that case also FECoff should be set to '1').

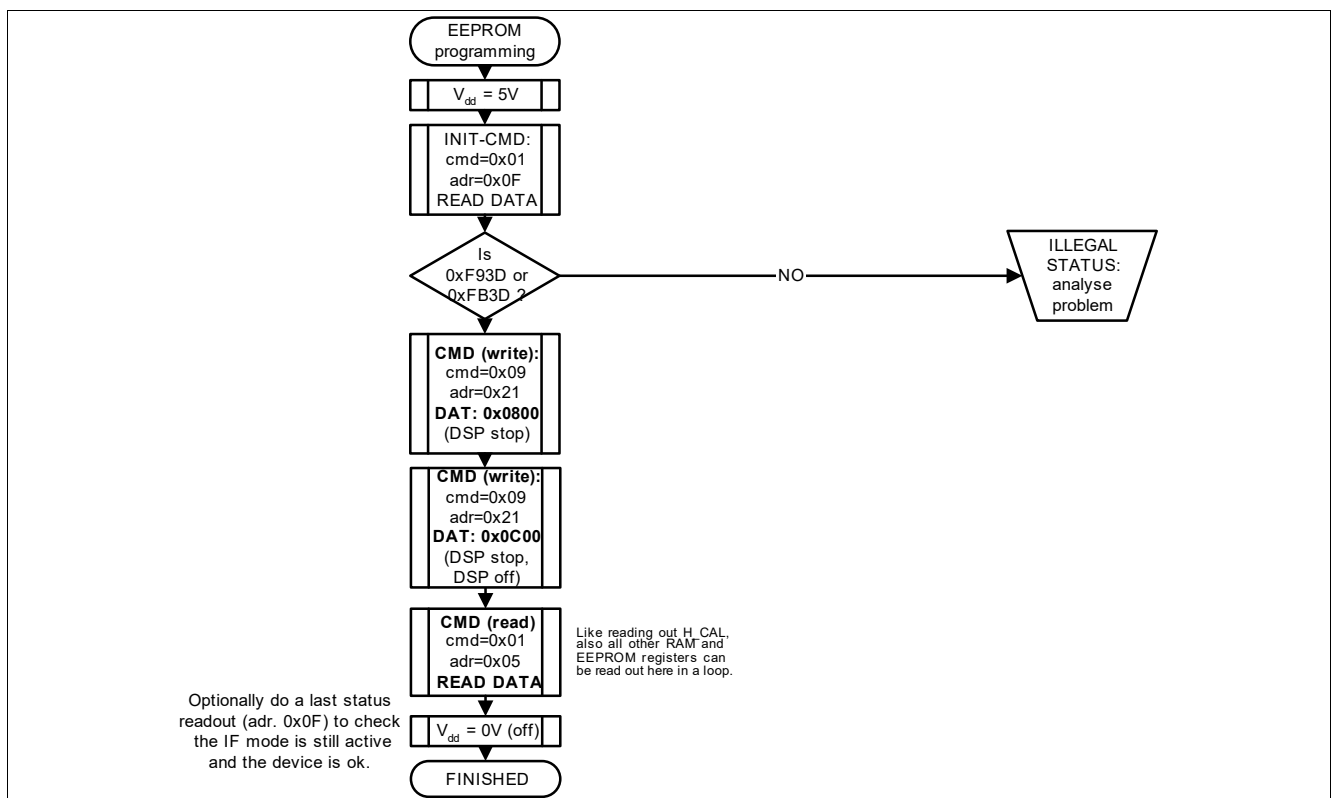**Figure 3-15 Basic data access flow**

Flowchart description:

1. Switch on the device
2. Send an inital command (status register readout)
3. Read the status data,check that the device is valid and the EEPROM content is valid
4. Set the test register: DSP stop=1 (see previous chapter)
5. Set the test register: DSP stop=1 DSP off=1 (see previous chapter)
6. Send a read command (HCAL)
   – Read the data word

– This readout might be looped for reading out also other parameters (like TCAL)
7. Check the status register again

Note: This routine can be merged with other (exemplary shown) routines. In that case only one initial frame (the very first interface access) is required after power-on.

3.6.8 Temporary overwrite of EEPROM data

Following steps are required to readout other internal data like the calibrated temperature and Hall value (as shown below **Table 3-16**). As the error correction stays disabled, it is not necessary to use correct parity values for this temporary setup. In case the parity is always corrected (and it is desired to check the complete behavior and correct EEPROM array calculation), the "FECoff" bit could be switched off again after the temporary EEPROM write.
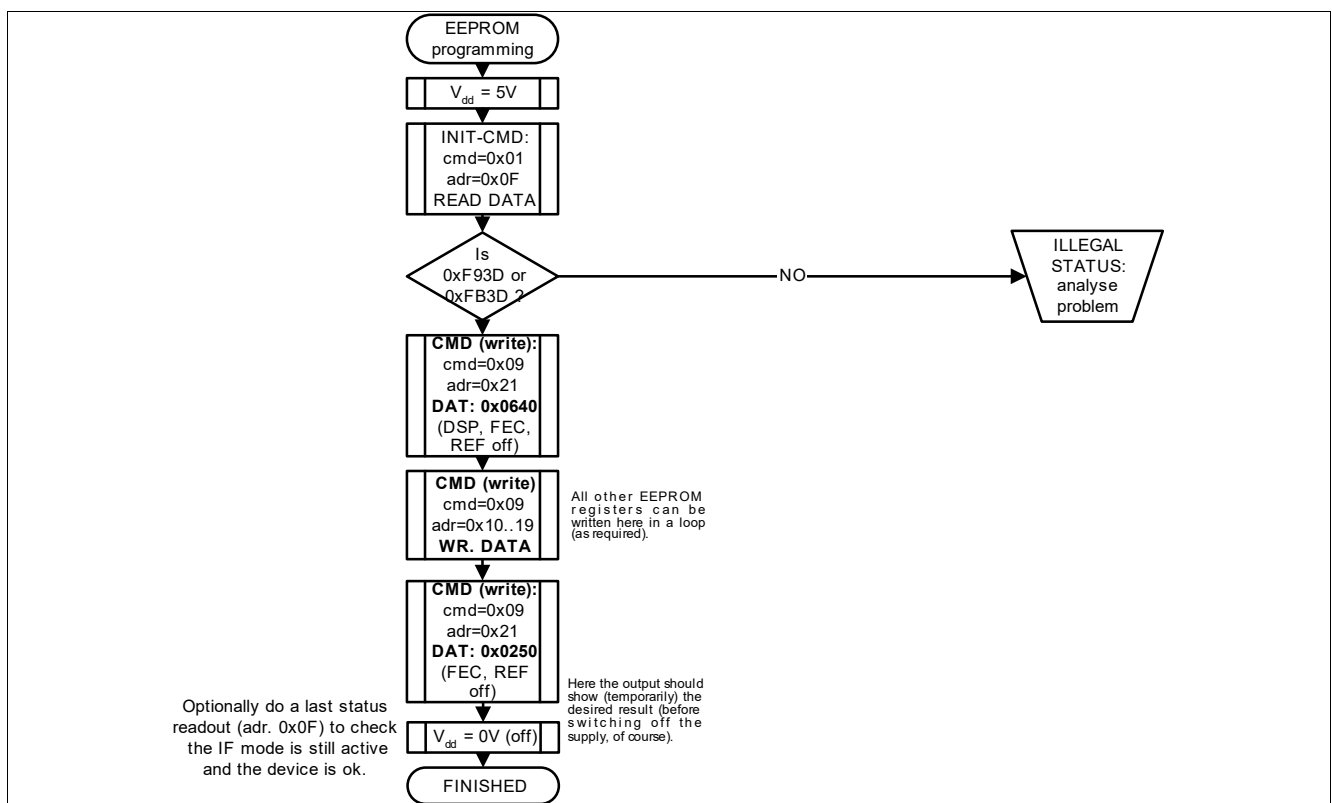
Figure 3-16 Basic EEPROM register overwrite flow

Flowchart description:

1. Switch on the device
2. Send an inital command (status register readout)
3. Read the status data,check that the device is valid and the EEPROM content is valid
4. Set the test register: DSP off=1 FEC off=1 REF off=1 (see previous chapter)
5. Send a write command (for any EEPROM register)
   Send the data words (in 16bit format, MSBs containing the parity may be kept '0')
6. Set the test register: FEC off=1 REF off=1 (see previous chapter)
   - The device is now temporarily working with the new EEPROM setting.
7. Check the status register again

3.6.9 DAC setup example

To find the exact DAC value for a desired output voltage (e.g. to set up the clamping low/high registers with the best available accuracy), it is possible to set the DAC value directly and to measure the result on the output pin.
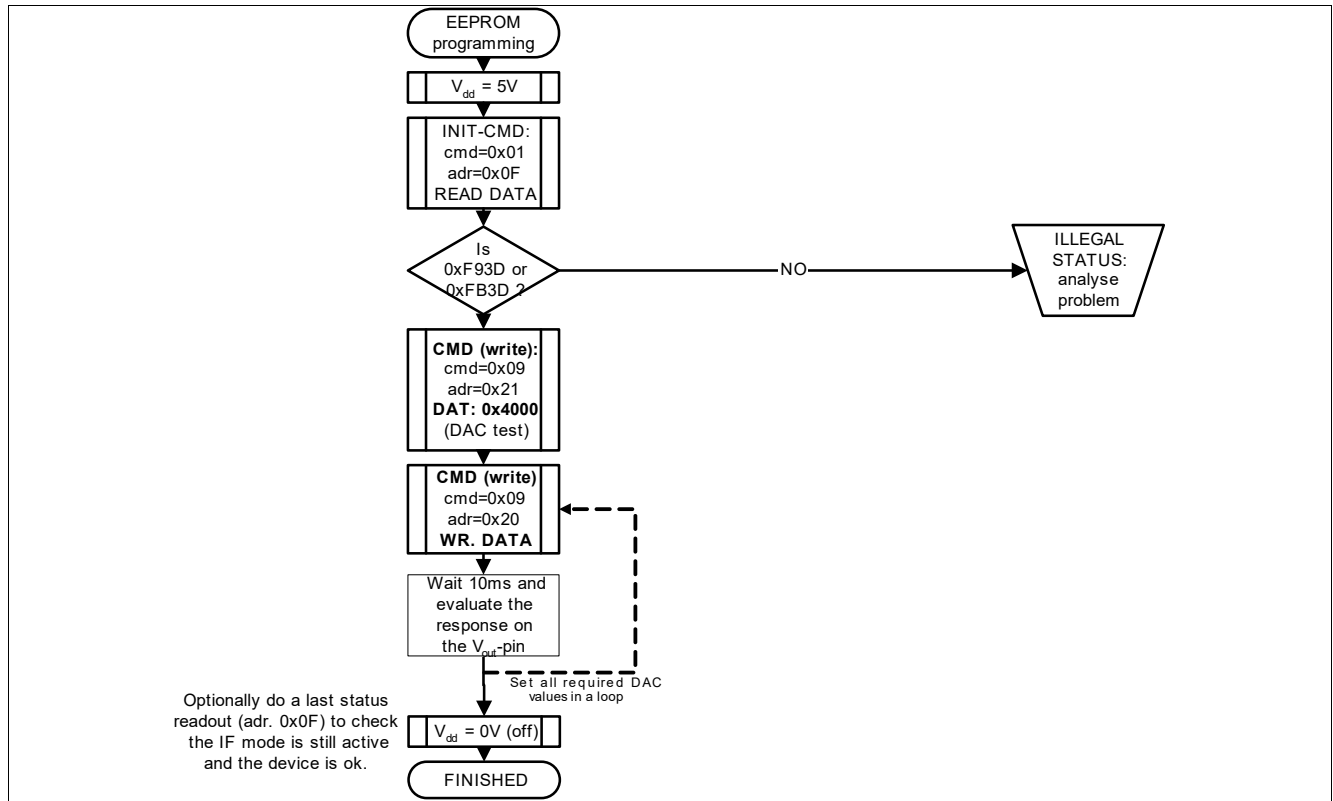
Figure 3-17 Basic DAC setup flow

Flowchart description:

1. Switch on the device
2. Send an inital command (status data readout)
3. Read the status data,check that the device is valid and the EEPROM content is valid
4. Set the test register: "DAC Test"=1 (see previous chapter)
   - The output immediately shows the content given by the DAC_SET register.
5. Send a write command (DAC_SET register)
   - Send the data word for the desired 12bit DAC value (in 16bit format, MSBs are '0')
   - The output changes accordingly to the new DAC value in DAC_SET
6. After 10ms (max. output setup time), measure Vout
   - Repeat writing a new DAC value (continue at step 5) until the response of all desired DAC values are measured
7. Check the status register again

4 Configuration & Calibration Parameters

This chapter describes the configuration and calibration parameters that can be set in the EEPROM of the TLE4997 (see EEPROM map, **Chapter 3.5**)

4.1 Magnetic Field Range - R

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:

$$\text{Gain} = \frac{(G - 16384)}{4096} \tag{4.1}$$

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 40mV/mT. Infineon pre-calibrates the samples to 60mV/mT..
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 voltage with zero field at the sensor. The offset value can be calculated by:

$$V_{OS} = \frac{(OS - 16384)}{4096} \times V_{DD} \tag{4.2}$$

Table 4-3   Offset

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Offset range[1]	V_{OS}	-400	–	399	$\%V_{DD}$	
Offset quantization steps	ΔOUT_{OS}	–	1.22	–	mV	at V_{DD} = 5V generally V_{DD}/4095

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.

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 78 Hz to 1320 Hz (from left to right). The update rate of the low-pass filter output is nominally 16 kHz.

Attention: The bit arrangement of the LP-Filter register is "0,2,1" (see EEPROM map in Figure 3-13). Therefore, the bits have to be rearranged accordingly to obtain the desired configuration. For example, the LP-filter setting "6" corresponds to the binary "011" in the LP-filter register.

Table 4-4   Low Pass Filter Setting

Parameter LP	Nominal cutoff frequency in Hz (-3 dB point)
0	78
1	244
2	421
3	615
4	826
5	1060
6	1320
7	Off
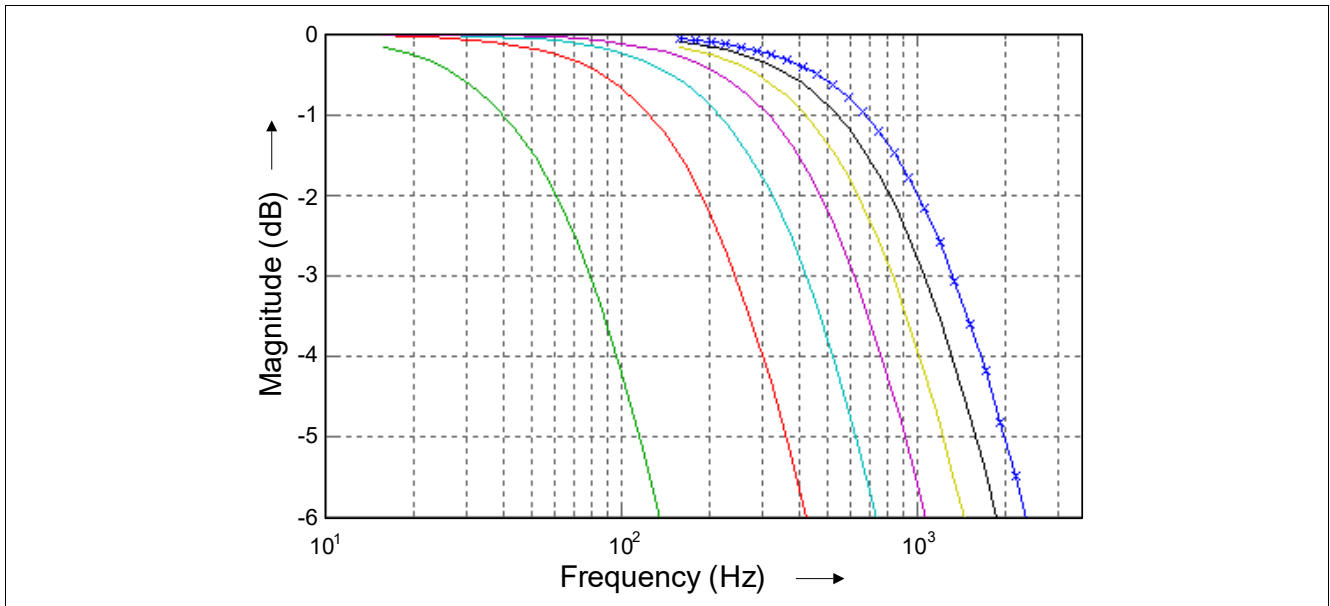
Figure 4-1   DSP Input Filter (Magnitude Plot)

Table 4-5   Low-Pass Filter

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	**Typ.**	**Max.**		
Corner frequency variation	Δf	-25	–	+25	%	–

4.5   DAC Input Interpolation Filter

An interpolation filter is placed between the DSP and the output DAC. This filter determines the frequency behavior of theTLE4997 in case the DSP input filter is disabled input filter is disabled . The update rate after interpolation filter is 256 kHz

Figure 4-2   DAC Input Filter (Magnitude Plot)

4.6   Clamping - CH, CL

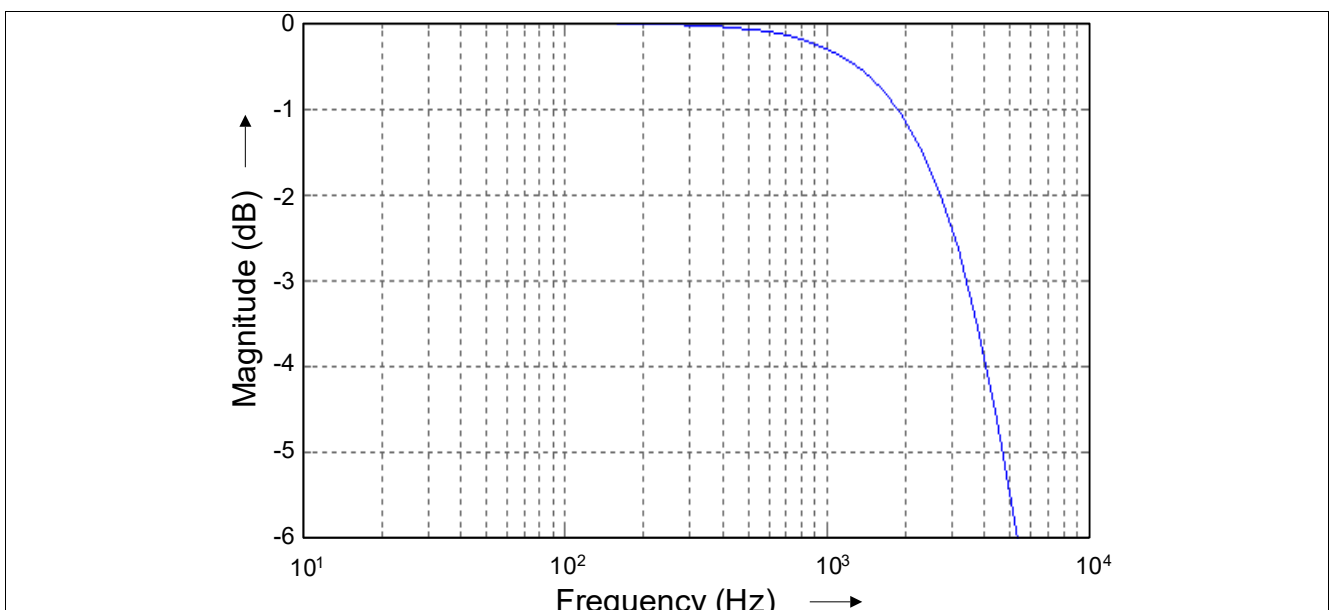The clamping function is useful for separating the output range into an operating range and error ranges. If the magnetic field is exceeding the selected measurement range, the output voltage V_{OUT} is limited to the clamping values. Any value in the error range is interpreted as an error by the sensor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

Figure 4-3 shows an example in which the magnetic field range between B_{min} and B_{max} is mapped to voltages between 0.8 V and 4.2 V.
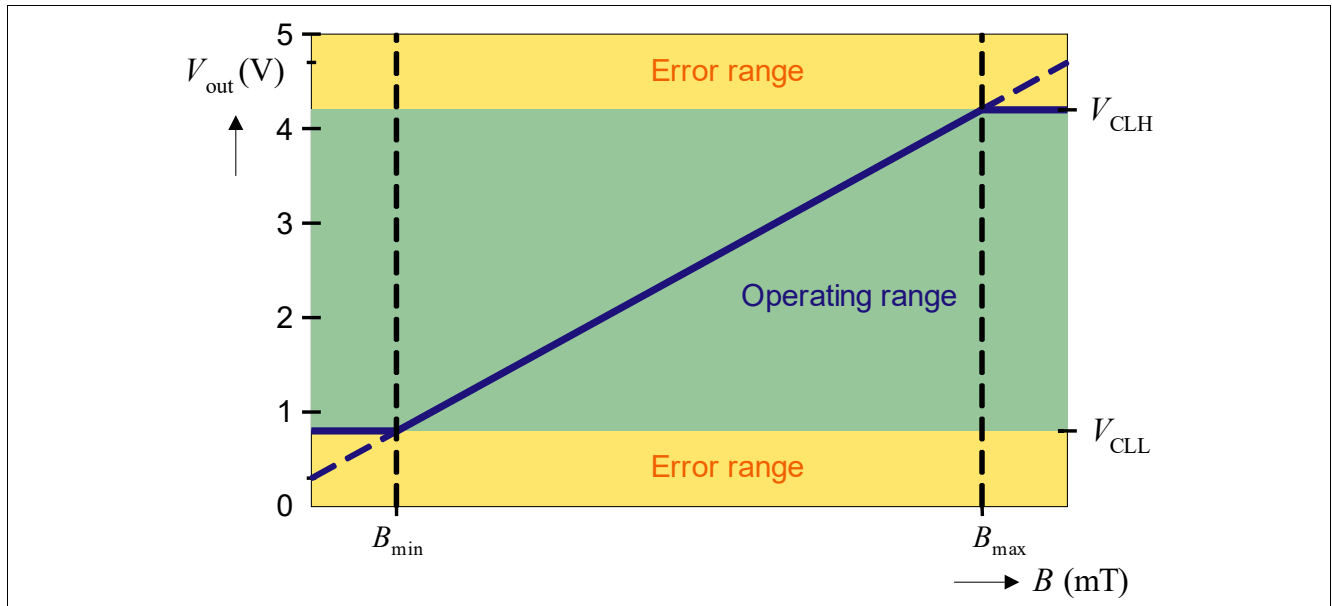
Figure 4-3   Clamping Example

Clamping - TLE4997 :

Table 4-6   Clamping

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	**Typ.**	**Max.**		
Clamping low[1]	V_{CLL}	0	–	99.98	$\%V_{DD}$	
Clamping high[1]	V_{CLH}	0	–	99.98	$\%V_{DD}$	
Clamping quantization steps	ΔV_{CLQ}	–	1.22	–	%mV	at V_{DD} = 5 V
Clamping voltage drift	ΔV_{CL}	-15		15	mV	in lifetime[2] over temperature[2]

1)   If clamping is set it must be within the allowed output range.

2) Valid in the range (5% of V_{DD}) < V_{OUT} <(95% of V_{DD}) for $T_{J \leq}$ 120°C
and (6% of V_{DD}) < V_{OUT} < (94% of V_{DD}) for 120°C < $T_{J} \leq$ 150°C

The clamping values are calculated by:

Clamping low voltage :

$$V_{CLL} = \frac{CL}{4096} \times V_{DD} \qquad\qquad\qquad (4.3)$$

Clamping high voltage:

$$V_{CLH} = \frac{CH}{4096} \times V_{DD} \tag{4.4}$$

4.7 Temperature Compensation - TL, TQ & TT

The TLE4997 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 TLE4997 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 a given magnet characteristic is described in **Chapter 5**.

Table 4-7   Temperature Compensation

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
1st order coefficient TC_1	TC_1	-1000	–	3000	ppm/ °C	[1]
Quantization steps of TC_1	ΔTC_1	–	15.26	–	ppm/ °C	–
2nd order coefficient TC_2	TC_2	-6	–	6	ppm/ °C²	[2]
Quantization steps of TC_2	ΔTC_2	–	0.119	–	ppm/ °C²	–
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 Calibration of TLE4997 Temperature Compensation

A temperature compensation mechanism is implemented in the TLE4997 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 TLE4997 is pre-configured by Infineon to have a constant magnetic sensitivity over temperature.

In case the TLE4997 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 TLE4997 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 TLE4997 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 TLE4997 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 TLE4997 has to be adapted to the permanent magnet employed in the application.

5.1 Integrated Temperature Polynomial

The integrated temperature compensation of the TLE4997 uses a third order polynomial, as shown in **Equation (5.1)**.

$$S_{DSP}(TCAL) \ = \ 1 + \frac{TL-160}{8 \cdot 8192} \cdot \left(\frac{TCAL}{16}\right) + \frac{TQ-128}{1024 \cdot 8192} \cdot \left(\frac{TCAL}{16}\right)^2 + \frac{TT-64}{131072 \cdot 8192} \cdot \left(\frac{TCAL}{16}\right)^3$$

(5.1)

with:

$$TCAL \ = \ 16 \cdot (T_J - 48)$$

(5.2)

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 3.5** 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.

5.2 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 5.3**). The application sensitivity polynomial is given by **Equation (5.3)**.

$$S_{App}(T_J) \ = \ 1 + TC_1(T_J - T_0) + TC_2(T_J - T_0)^2$$

(5.3)

T_J is the junction temperature in °C, TC_1 (in ppm/°C) and TC_2 (in ppm/°C^2) are the first and second order application temperature coefficients and T_0 (in °C) is a reference temperature.
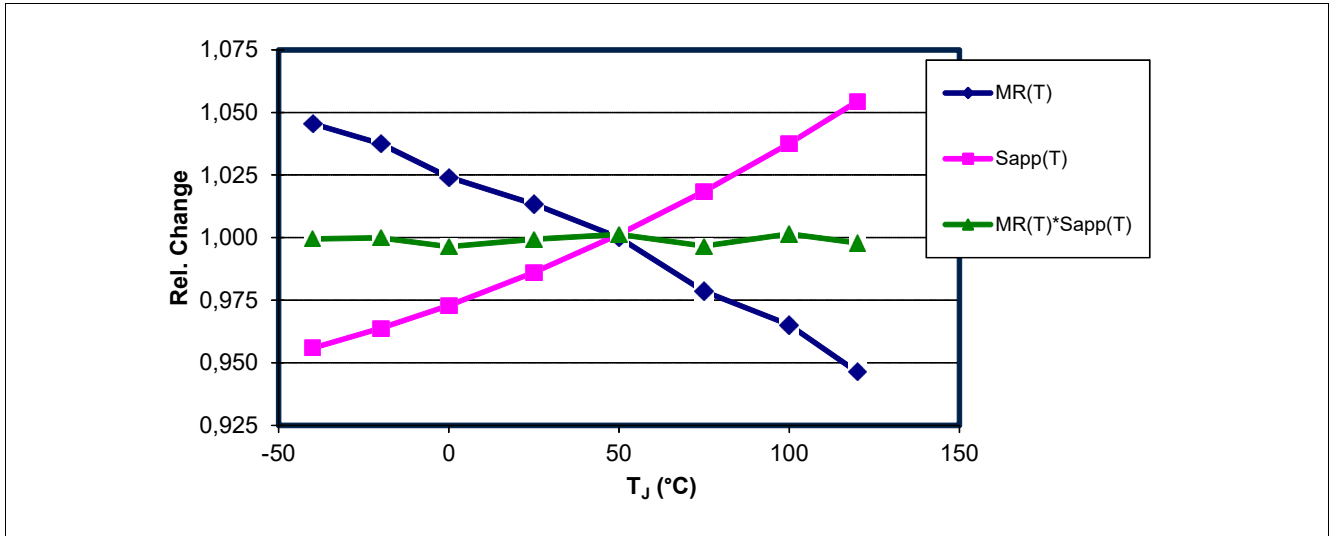
Figure 5-1 **Example thermal behavior of magnetic remanence M(T) and application sensitivity polynomial $S_{app}(T)$ with reference temperature 48°C.**

The reference temperature T_0 is a degree of freedom that can be chosen by the user, such that the gain of the TLE4997 that is configured in the EEPROM, applies at this reference temperature.

In case the calibration of the offset and gain for the output charateristic 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 $T_0 = 48°C$ is recommended for simplicity (to match the reference temperature in the definition of TCAL in **Equation (5.2)**).

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 (5.4)** and illustrated in **Figure 5-1**.

$$S_{App}(T_J) \cdot M_R(T_A) \approx \mathrm{constant} \tag{5.4}$$

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 (5.5)**.

$$T_J = T_A + R_{th} \cdot (U \cdot I) \tag{5.5}$$

R_{th} is the thermal resistance of the TLE4997 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 (5.6)**.

$$S_{DSPfinal}(T_J) \approx S_{DSPpre}(T_J) \cdot S_{App}(T_J) \tag{5.6}$$

$S_{DSPfinal}(T_J)$ is the integrated temperature polynomial given by the combination of **Equation (5.1)** and **Equation (5.2)**, 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 (5.6)** and programmed into the TLE4997.

5.3 Determination of Sensitivity Polynomial from Measurement

For the determination of the Coefficients for the application sensitivity polynomial (**Equation (5.3)**) 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 TLE4997 and a moveable permanent magnet is shown in **Figure 5-2**.

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.
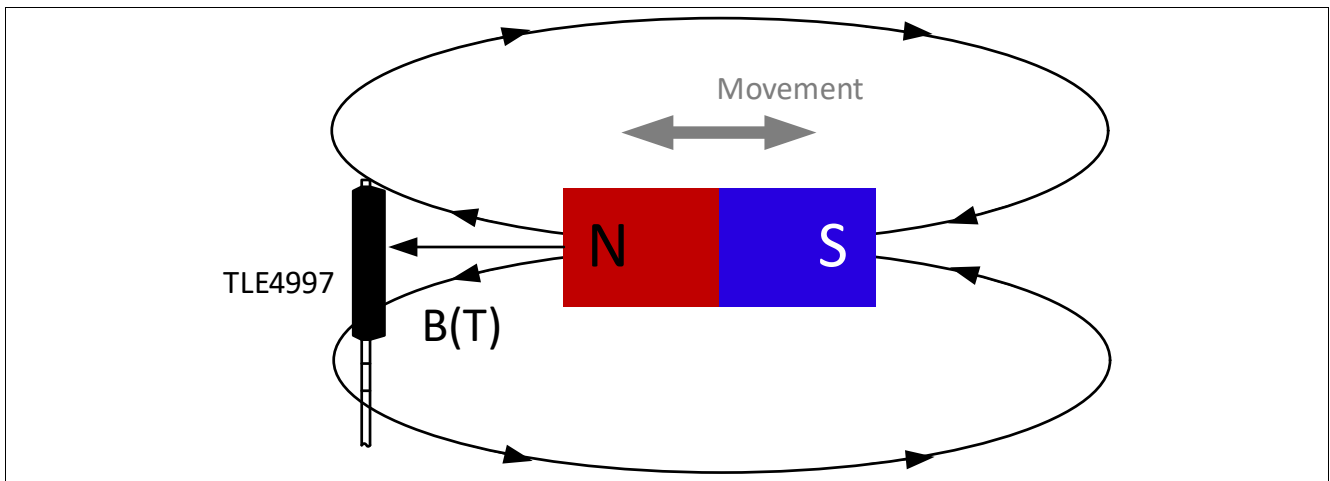
Figure 5-2   Example Position Sensing Application

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 densitiy 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 $VDAC^{(i)}$ value via the programming interface.
- For each data point, calculate the compensation sensitivity value $S^{(i)}$ from the $VDAC^{(i)}$ value and the output value at zero field $VDAC_0$, using **Equation (5.7)**

$$S^{(i)} = \frac{VDAC_0}{VDAC^{(i)} - VDAC_0}$$
(5.7)

- 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 5-3**).

Figure 5-3 Example Polynomial Fit Procedure.

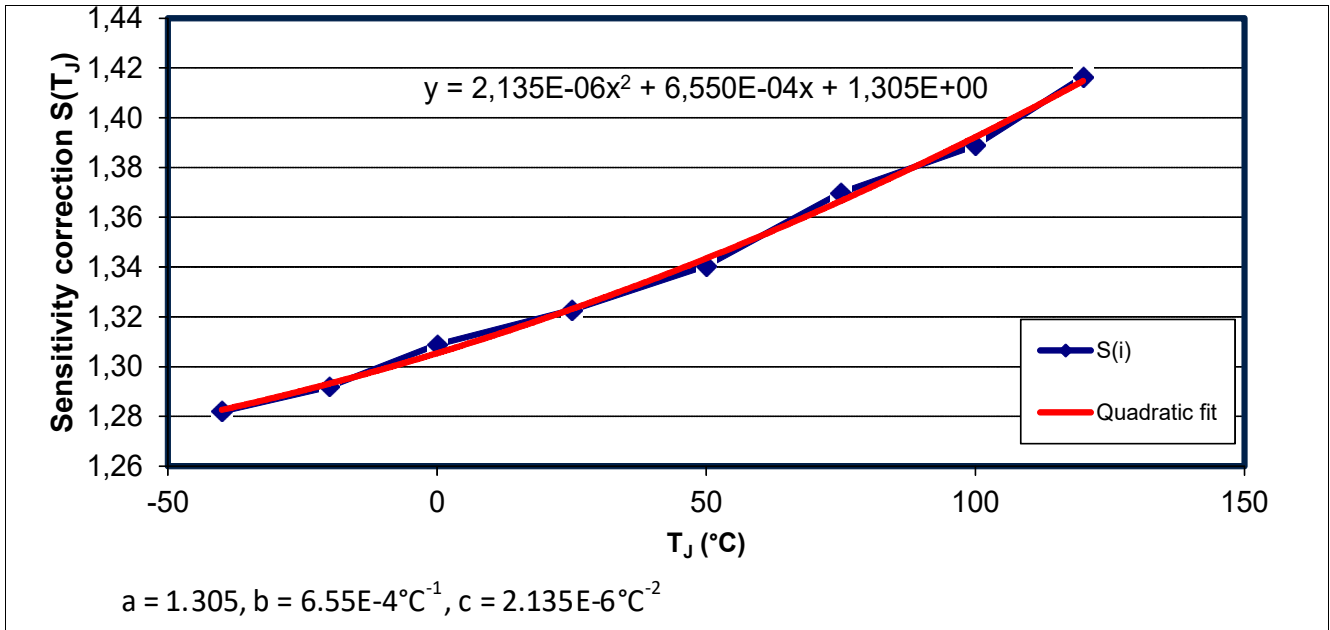- Derive the coefficients of the application sensitivity polynomial from the parameters a, b, and c obtained from the quadratic fit using **Equation (5.8)** and **Equation (5.9)**.

$$TC_1 = \frac{b + 2 \cdot c \cdot T_0}{a + b \cdot T_0 + c \cdot T_0^2} \tag{5.8}$$

$$TC_2 = \frac{c}{a + b \cdot T_0 + c \cdot T_0^2} \tag{5.9}$$

5.4   Calculation of Final Temperature Compensation Parameters

After determination of the application sensitivity polynomial S_{app}, it is necessary to adapt the temperature compensation paramters TL and TQ in the EEPROM such that the overall sensitivity of the TLE4997 shows the desired increase over temperature to compensate for the thermal reduction of the magnet's remanence in the application.

5.4.1   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 (5.6)**. To find this parameter set, an error function $\varepsilon(T)$ is defined in that is minimized in an iterative procedure.

$$\varepsilon(T_J) = \frac{S_{DSPfinal}(T_J)}{C \cdot S_{DSPpre}(T_J) \cdot S_{app}(T_J)} - 1 \tag{5.10}$$

$S_{DSPfinal}(T_J)$ is the integrated temperature polynomial given by the combination of **Equation (5.1)** and **Equation (5.2)**, 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 (5.10)** 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 (5.11)** is minimized.

$$\varepsilon_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\varepsilon(T_J^{(i)}))^2}$$

(5.11)

5.4.2 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: TR_pre: 0...7; 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_app = 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 - 64) * ((T -48) ^ 3) / 131072 / 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-64) * ((T - 48) ^ 3) / 131072 / 8192
End Function
```

For the algorithm we need the already explained error function:

```
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 = 500
        TL_step = 10
        TQ_lo = 0
        TQ_hi = 240
        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.Sqr(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 TL_{final} and TQ_{final} contain the optimum values for TL and TQ. These values shall be programmed into the sensor's EEPROM.

5.5 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 5-4**).

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

1. Measure the sensor's AOUT and TCAL registers at a fixed magnet position for different temperatures as described in **Chapter 5.3**, enter the T_J (in °C) and AOUT (in V) values in the table fields marked in yellow (see **Figure 5-4**, upper left side). For the readout of this data, the Infineon TLE4997 Evaluation Kit can be used.
2. The tool automatically calculates the corresponding Sensitivity correction values S from the entered T_J and AOUT values according to **Equation (5.7)**.
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 5-4**, upper right side).
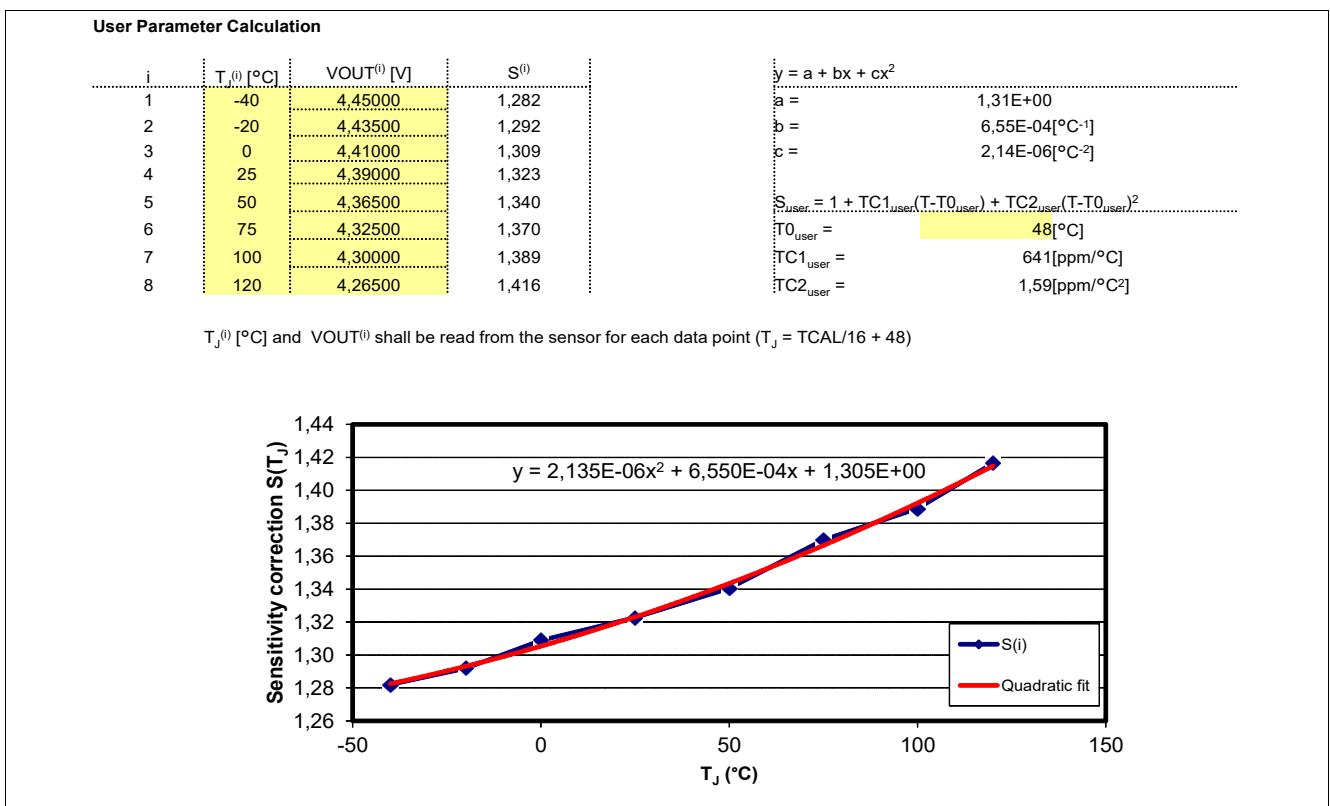

User Parameter Calculation

i	$T_J^{(i)}$ [°C]	$VOUT^{(i)}$ [V]	$S^{(i)}$
1	-40	4,45000	1,282
2	-20	4,43500	1,292
3	0	4,41000	1,309
4	25	4,39000	1,323
5	50	4,36500	1,340
6	75	4,32500	1,370
7	100	4,30000	1,389
8	120	4,26500	1,416

$y = a + bx + cx^2$

a = 1,31E+00
b = 6,55E-04[°C^{-1}]
c = 2,14E-06[°C^{-2}]

$S_{user} = 1 + TC1_{user}(T-T0_{user}) + TC2_{user}(T-T0_{user})^2$

$T0_{user}$ = 48[°C]
$TC1_{user}$ = 641[ppm/°C]
$TC2_{user}$ = 1,59[ppm/°C^2]

$T_J^{(i)}$ [°C] and $VOUT^{(i)}$ shall be read from the sensor for each data point (T_J = TCAL/16 + 48)

$y = 2,135E-06x^2 + 6,550E-04x + 1,305E+00$

Figure 5-4 Infineon tool for temperature calibration, application sensitivity polynomial fit.

4. Readout the sensor's preprogrammed TL_{pre} and TQ_{pre} values and enter them in the corresponding table fields marked in yellow (see **Figure 5-5** upper left side). For the readout of this data, the Infineon TLE4997 Evaluation Kit can be used.
5. 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 5.4**. The calculated values TL_{final} and TQ_{final} appear in the corresponding table fields marked in green (see **Figure 5-5** upper right side)
6. Program the calculated TL_{final} and TQ_{final} values into the TLE4997 using the Infineon TLE4997 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 succesful calibration, $S_{DSP,final}$ should by approximately equal $S_{DSP,pre}*S_{app}$ (compare **Equation (5.6)**).

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%.

New DSP Parameter Calculation

			$T0_{user}$ =	48	[°C]		TL_{final} and TQ_{final} are calculated automatically by VB script:
Input:			$TC1_{user}$ =	6,41E-04	[°C⁻¹]		
TL_{pre} =	166	(0 to 511)	$TC2_{user}$ =	1,59E-06	[°C⁻²]		TL_{final} = 209
TQ_{pre} =	162	(0 to 255)					TQ_{final} = 175
TT_{pre} =	28	(0 to 31)					TT_{final} = 28

TL_{pre} and TQ_{pre} shall be read from the sensor via the programming interface
TT is fixed by Infineon to value 28 (leaded package devices) or 21 (SMD devices)

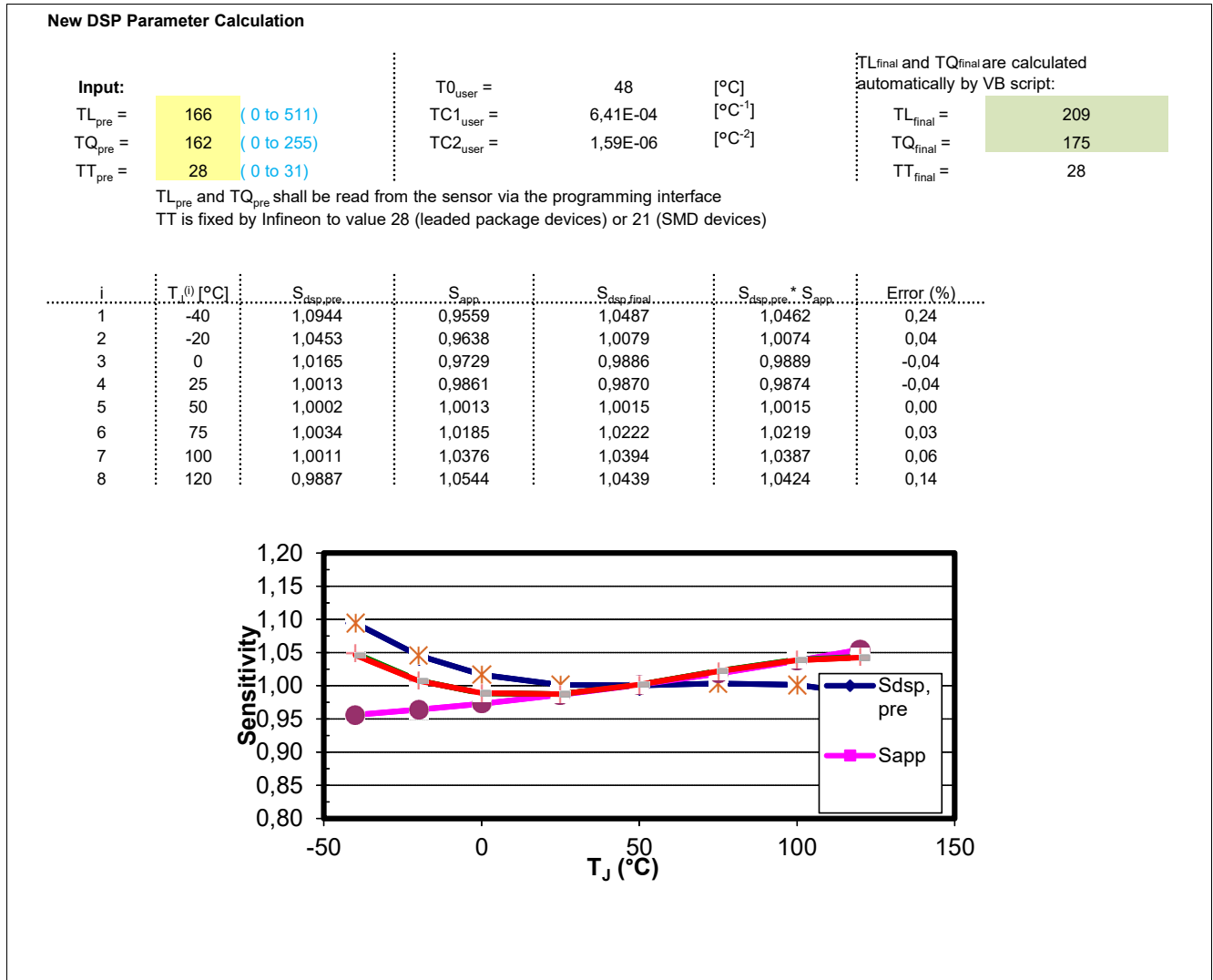| i	$T_J^{(i)}$ [°C]	$S_{dsp,pre}$	S_{app}	$S_{dsp,final}$	$S_{dsp,pre} * S_{app}$	Error (%)
1	-40	1,0944	0,9559	1,0487	1,0462	0,24
2	-20	1,0453	0,9638	1,0079	1,0074	0,04
3	0	1,0165	0,9729	0,9886	0,9889	-0,04
4	25	1,0013	0,9861	0,9870	0,9874	-0,04
5	50	1,0002	1,0013	1,0015	1,0015	0,00
6	75	1,0034	1,0185	1,0222	1,0219	0,03
7	100	1,0011	1,0376	1,0394	1,0387	0,06
8	120	0,9887	1,0544	1,0439	1,0424	0,14

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

Note: Error (%) is the deviation of $S_{dsp,final}$ from the product of $S_{dsp,pre}$ times S_{app}

6 Calibration of TLE4997 Output Characteristic

In a position sensing application, the maximum and minimum magnetic field sensed by the TLE4997 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 TLE4997 so the possible analog output range is matched to the magnetic input range that is available in the application.

6.1 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 TLE4997 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 6-1**.
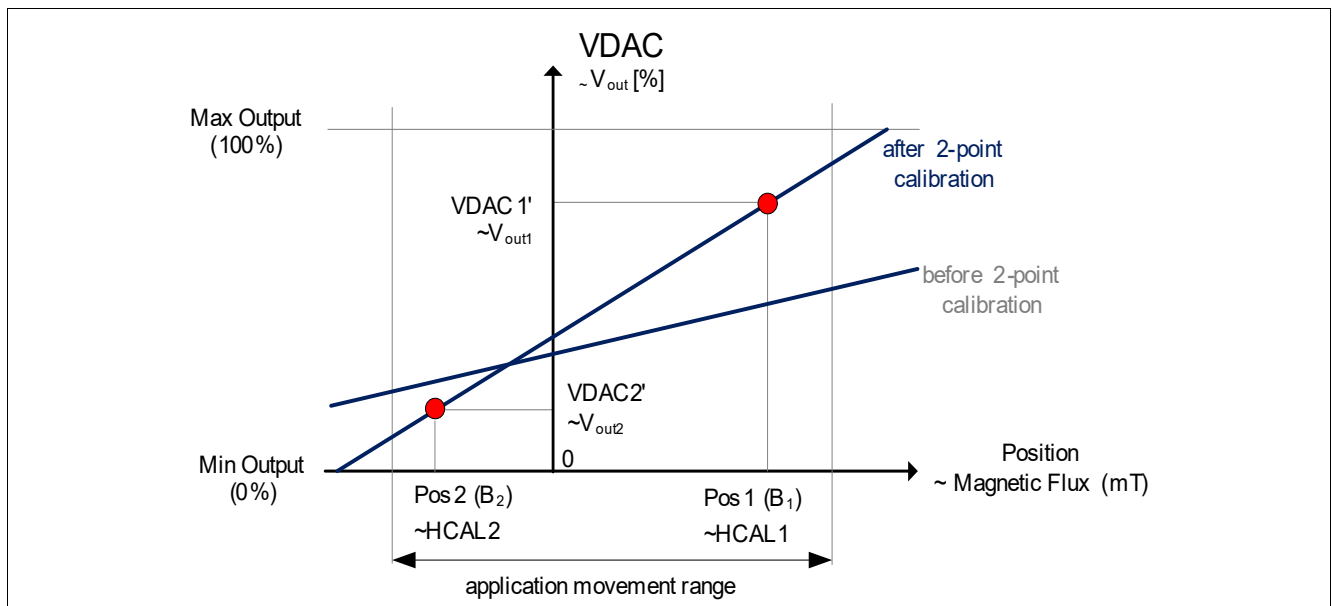

Figure 6-1   Schematic of Two-Point Calibration

The value VDAC is calculated in the TLE4997 with the configured offset (OS) and gain (G) value according to **Equation (6.1)**.

$$\mathrm{VDAC} = \frac{(G - 16384) \cdot \mathrm{HCAL}}{32768} + OS - 16384 \qquad (6.1)$$

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. Chose the desired output signals VDAC1' and VDAC2' 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.
4. Fix the application module in position Pos2 and read the HCAL register via the programming interface. This value is HCAL2.

5. Calculate the according gain and offset parameters from the recorded HCAL1 and HCAL2 values and the desired VDAC1' and VDAC2' values using **Equation (6.2)** and **Equation (6.3)**.

$$G \; = \; 16384 + 32768 \cdot \frac{VDAC2' - VDAC1'}{HCAL2 - HCAL1} \tag{6.2}$$

$$OS \; = \; 16384 + VDAC1' - \frac{(G - 16384) \cdot HCAL1}{32768} \tag{6.3}$$

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

Attention: HCAL is a 16bit signed integer value in the range of ±30000. VDAC is a 12bit unsigned decimal value applied to the internal DAC for the ratiometric output stage. The value range is from 0 to 4095 and corresponds to 0% to 100% of VDD..

6.2 Two-Point Calibration Examples

6.2.1 Calibration with Application Readout

Optimum accuracy of the TLE4997 can be achived 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 VOUT values. The registers can be read using the TLE4997 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 VOUT1' = 0.25V (5% of the full 5V range) at position x_1 and VOUT2' = 4.75V (95% of full 5V range) at position x_2 .

The measured HCAL and desired VOUT' values are shown in **Table 6-1**

Table 6-1   Example VOUT and HCAL values for 2-point calibration

Position	measured HCAL (Hex)	HCAL (Dec, signed) Range ±30000	desired VOUT' (V)	desired VDAC'(Hex)	VDAC' (Dec) Range 0 to 4095
x_1	$EAC5_H$	-5435	0.25	CD_H	205
x_2	$183B_H$	6203	4.75	$F32_H$	3890

Applying the HCAL and VDAC' values form **Table 6-1** in **Equation (6.2)** and **Equation (6.3)** yields:

$$G \; = \; 16384 + 32768 \cdot \frac{(3890 - 205)}{(6203 - (-5435))} \; = \; 26759 \tag{6.4}$$

$$OS \; = \; 16384 + 205 - \frac{(26759 - 16384) \cdot (-5435)}{32768} = \; 18310 \tag{6.5}$$

This corresponds to a multiplicative gain of 2.53 and an offset of 2.35V, according to the formulas in **Chapter 4**.

Attention: If the measured HCAL values are close to the range limits ±30000, saturation takes place. In this case, it is recommended to switch to a higher magnetic range (±100 or ±200 mT) prior to the calibration.

6.2.2 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, which needs to be mapped to 4.5V and 0.5V, the clamping levels must be set to 4.7V and 0.3V.

The precalibrated gain value is 1.62 and the precalibrated offset value is 50% (sensor read-out).

The +/- 100mT default range is well suited, as both magnetic flux values are well within the allowed range.

The sensitivity needs to be set in that way that the magnetic flux change from B_2 = -25mT to B_1 = +75mT results in a voltage change from V_{out2} = 0.5V to V_{out1} = 4.5V.

So the required sensitivity is $(V_{out1} - V_{out2})/(B_1 - B_2)$ = (4.5-0.5) / (+75-(-25)) = 0.04 V/mT = 40mV/mT.

As the default sensitivity is about 60mV/mT, the gain value needs to be lowered by a factor of (40 / 60) = 0.667. So the gain must be reprogrammed to (1.62 x 0.667) = 1.08.

For the offset setup, we can proceed as follows:

A magnetic flux of 75mT will cause with the new sensitivity value of 40mV/mT a output change of (75 x 40) = 3000 mV = 3V.

With the default offset setup of 2.5V we would see on the output (only theoretically) 5.5V, but we need 4.5V. So the offset value needs to be lowered by (5.5-4.5) = 1V.

This corresponds to an ratiometric percentage of (1/5) x 100% = 20%. So it is necessary to set the new offset to (50 - 20) = 30 %.

The clamping parameters need to be set to (0.3 / 5) x 100% = 6% and (4.7 / 5) x 100% = 94% to provide the required output limits.

Revision History

Page or Item	Subjects (major changes since previous revision)
v01_01, 2019-08	
Page 35	Corrected **Equation (6.3)**
Page 35	Corrected **Equation (6.5)**
Page 35	Corrected offset value in the paragraph

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