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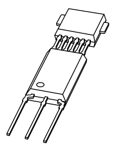


KMA199

Programmable angle sensor

Rev. 2 — 7 December 2011 Product data sheet

1. Product profile

1.1 General description

The KMA199 is a magnetic angle sensor system. The MagnetoResistive (MR) sensor bridges and the mixed signal Integrated Circuit (IC) are integrated into a single package.

This angular measurement system KMA199 is pre-programmed, pre-calibrated and therefore, ready to use.

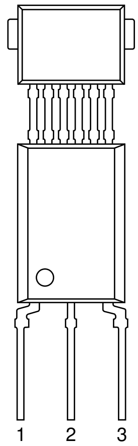
The KMA199 allows user specific adjustments of angular range, zero angle and clamping voltages. The settings are stored permanently in an Electrically Erasable Programmable Read-Only Memory (EEPROM).

1.2 Features and benefits

- High precision sensor for magnetic angular measurement
- Automotive qualified in accordance with AEC-Q100
- Programmable user adjustments, including zero angle and angular range
- Fail-safe EEPROM
- Independent from the magnetic field strength above 35 kA/m
- User-programmable 32-bit identifier
- Ready to use
- Ratiometric analog output voltage
- Single package sensor system
- High temperature range up to 160 °C
- Built-in transient protection
- Programming via One-Wire Interface (OWI)
- Magnet-loss and power-loss detection
- Factory calibrated

2. Pinning information

Table 1. Pinning

Pin	Symbol	Description	Simplified outline
1	V_{DD}	supply voltage	
2	GND	ground	
3	OUT/DATA	analog output or data interface	

3. Ordering information

Table 2. Ordering information

Type number	Package		
	Name	Description	Version
KMA199	-	plastic single-ended multi-chip package; 6 interconnections; 3 in-line leads	SOT880

4. Functional diagram

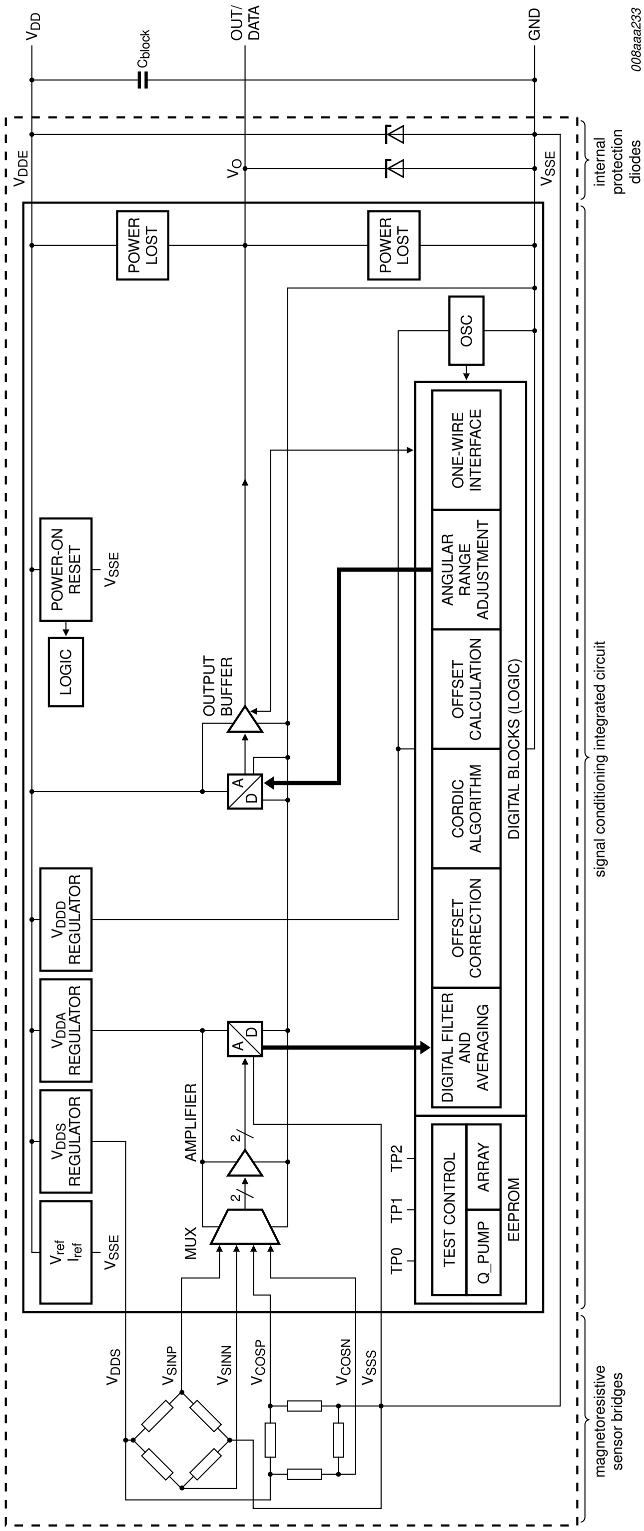


Fig 1. Functional diagram of KMA199

5. Functional description

The KMA199 amplifies two orthogonal differential signals which are delivered by MR sensor bridges and converts them into the digital domain. The angle is calculated using the COordinate Rotation DIgital Computer (CORDIC) algorithm. After a digital-to-analog conversion the analog signal is provided to the output. Thus, the output is a linear representation of the angular value. Zero angle, clamping voltages and angular range are programmable. In addition, two 16-bit registers are available for customer purposes, like sample identification.

The KMA199 comprises a Cyclic Redundancy Check (CRC) and an Error Detection and Correction (EDC) supervision, as well as a magnet-loss detection to ensure a fail-safe operation. A power-loss detection circuit pulls the analog output to the remaining supply line, if either the supply voltage or the ground line is interrupted.

After multiplexing the two MR Wheatstone bridge signals and their successive amplification, the signal is converted into the digital domain by an Analog-to-Digital Converter (ADC). Further processing is done within an on-chip state machine. This includes offset cancellation, calculation of the mechanical angle using the CORDIC algorithm, as well as zero angle and angular range adjustment. The internal Digital-to-Analog Converter (DAC) and the analog output stage are used for conversion of the angle information into an analog output voltage, which is ratiometric to the supply voltage.

The configuration parameters are stored in an user-programmable EEPROM. The OWI (accessible using pin OUT/DATA) is used for accessing the memory.

5.1 Angular measurement directions

The differential signals of the MR sensor bridges depend only on the direction of the external magnetic field strength H_{ext}, which is applied parallel to the plane of the sensor. In order to obtain a correct output signal, the minimum saturation field strength has to be exceeded.

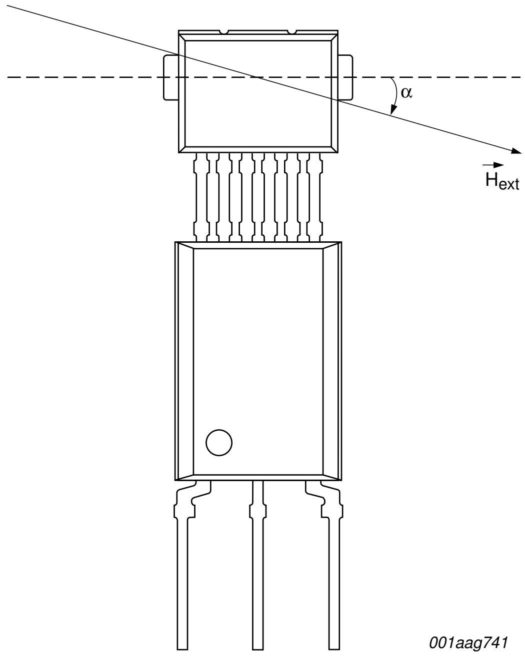


Fig 2. Angular measurement directions

Since the Anisotropic MR (AMR) effect is periodic over 180°, the sensor output is also 180°-periodic, where the angle is calculated relative to a freely programmable zero angle. The dashed line indicates the mechanical zero degree position.

6. Analog output

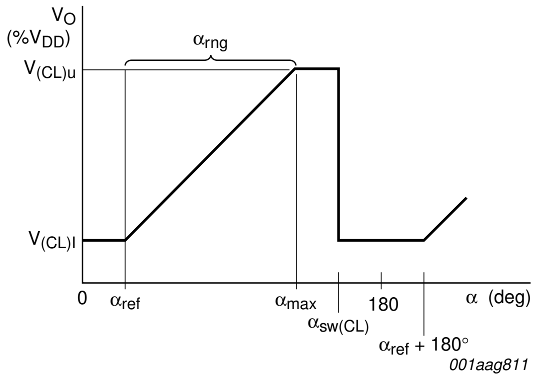
The KMA199 provides one analog output signal on pin OUT/DATA. The measured angle α is converted linearly into a value, which is ratiometric to the supply voltage V_{DD}. Either a positive or a negative slope is provided for this purpose.

The following table describes the analog output behavior for a positive slope. If for example, a magnetic field angle, above the programmed maximum angle α_{max}, but below the clamp switch angle $\alpha_{sw(CL)}$ is applied to the sensor, then analog output is set to the upper clamping voltage. If the magnetic field angle is larger than the clamp switch angle, the analog output switches from upper to lower clamping voltage. In the case of a negative slope, the clamping voltages are changed.

Table 3. Analog output behavior for a positive slope

Magnetic field angle	Analog output
$\alpha_{max} < \alpha < \alpha_{sw(CL)}$	$V_{(CL)u}$
$\alpha_{sw(CL)} < \alpha < \alpha_{ref} + 180°$	$V_{(CL)l}$

The analog output voltage range codes both angular and diagnostic information. A valid angle value is between the upper and lower clamping voltage. If the analog output is in the diagnostic range, that is below 4 %V_{DD} or above 96 %V_{DD}, an error condition has been detected. The analog output repeats every 180°.



$\alpha_{max} = \alpha_{ref} + \alpha_{rng}$

Fig 3. Characteristic of the analog output

7. Diagnostic features

The KMA199 provides four diagnostic features:

7.1 EEPROM CRC and EDC supervision

The KMA199 system includes a supervision of the programmed data. At power-on, a CRC of the EEPROM is performed. Furthermore the EEPROM is protected against bit errors. Every 16-bit data word is saved internally as a 22-bit word for this purpose. The protection logic corrects any single-bit error in a data word, while the sensor continues in normal operation mode. Multiple bit errors per word will be detected and switches the device into diagnostic mode.

7.2 Magnet-loss detection

If the applied magnetic field strength is not sufficient, the KMA199 raises a diagnostic condition. In order to enter the diagnostic mode, due to EEPROM CRC or magnet-loss detection, the device can be programmed into active diagnostic mode, where the output is driven below 4 %V_{DD} or above 96 %V_{DD}.

7.3 Power-loss detection

The power-loss detection circuits enable the detection of an interrupted supply or ground line of the KMA199. In the case of a power-loss condition, two internal switches in sensor are closed, connecting the pin of the analog output with the supply voltage and the ground pins.

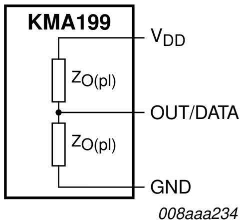


Fig 4. Equivalent output circuit in case of a power-loss condition

Table 4 shows the resulting output voltage depending on the error case and the load resistance.

Table 4. Power-loss behavior

Load resistance	Supply voltage lost	Ground lost
$R_L > 5$ kΩ	$V_O \leq 4\ \%V_{DD}$	$V_O \geq 96\ \%V_{DD}$

7.4 Low supply voltage detection

If the supply voltage is below the switch-off threshold voltage, a status bit is set.

Table 5 describes the behavior of the analog output at different supply voltages.

Table 5. Supply voltage behavior

Voltage range	Description	Analog output
0 V to ≈ 1.5 V	the output drives an active LOW, but the switches of the power-loss detection circuits are not fully opened and set the output to a level between ground and half the supply voltage	actively driven output to a voltage level between ground and half the supply voltage
≈ 1.5 V to V_{POR}	all modules begin to work and the power-on reset is active	diagnostics at LOW level
V_{POR} to $V_{th(on)}$ or $V_{th(off)}$	all modules begin to work and the digital part is initialized	EEPROM defined diagnostic level
$V_{th(on)}$ or $V_{th(off)}$ to 4.5 V	analog output is switched on after power-on time and represents the measured angle	analog output of the measured angle without the specified accuracy
4.5 V to 5.5 V	normal operation where the sensor works with the specified accuracy	analog output of the measured angle

8. Limiting values

Table 6. Limiting values
In accordance with the Absolute Maximum Rating System (IEC 60134).

Symbol	Parameter	Conditions		Min	Max	Unit
V_{DD}	supply voltage			−0.3	+5.7	V
		t_{init} < 200 h	[1]	-	6.0	V
V_O	output voltage		[2]	−0.3	V_{DD} + 0.3	V
I_r	reverse current	T_{amb} < 70 °C		-	150	mA
T_{amb}	ambient temperature			−40	+160	°C
$T_{amb(pr)}$	programming ambient temperature			10	70	°C
T_{stg}	storage temperature			−40	+125	°C
EEPROM						
$t_{ret(D)}$	data retention time	T_{amb} = 50 °C		17	-	year
$N_{endu(W\_ER)}$	write or erase endurance	$T_{amb(pr)}$ = 70 °C		100	-	cycle

[1] Time until sensor environment is initialized.

[2] The maximum value of the output voltage is 5.7 V.

9. Recommended operating conditions

Table 7. Operating conditions
In a homogenous magnetic field.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{DD}	supply voltage		[1]	4.5	5.0	5.5	V
T_{amb}	ambient temperature			−40	-	+160	°C
$T_{amb(pr)}$	programming ambient temperature			10	-	70	°C
C_L	load capacitance		[2]	0	-	22	nF
C_{block}	blocking capacitance		[3]	75	-	∞	nF
R_L	load resistance		[4]	5	-	∞	kΩ
H_{ext}	external magnetic field strength			35	-	-	kA/m

[1] Normal operating mode.

[2] Between ground and analog output, as close as possible to the package for improved electromagnetic immunity.

[3] Between ground and supply voltage, as close as possible to the package and with a low equivalent series resistance.

[4] Power-loss detection is only possible with a load resistance within the specified range connected to the supply or ground line.

10. Thermal characteristics

Table 8. Thermal characteristics

Symbol	Parameter	Conditions	Typ	Unit
$R_{th(j-a)}$	thermal resistance from junction to ambient		120	K/W

11. Characteristics

Table 9. Supply current

Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
I_{DD}	supply current		[1][2]	5	-	10	mA

[1] Normal operating mode.

[2] Without load current at the analog output.

Table 10. Power-on reset

Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
$V_{th(on)}$	switch-on threshold voltage	analog output switches on, if $V_{DD} > V_{th(on)}$	4.00	4.30	4.45	V
$V_{th(off)}$	switch-off threshold voltage	analog output switches off, if $V_{DD} < V_{th(off)}$	-	4.20	4.30	V
V_{hys}	hysteresis voltage	$V_{hys} = V_{th(on)} - V_{th(off)}$	0.1	-	0.4	V
V_{POR}	power-on reset voltage	IC is initialized	2.4	-	3.3	V

Table 11. System performance

Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
α_{res}	angle resolution		[1]	-	-	0.04	deg
α_{max}	maximum angle	programmable angular range for $V_{(CL)u} - V_{(CL)l} \geq 80\ \%V_{DD}$	[2]	5	-	180	deg
α_{ref}	reference angle	programmable zero angle	[2]	0	-	180	deg
$V_{O(nom)}$	nominal output voltage	at full supply operating range		5	-	95	$\%V_{DD}$
$V_{O(udr)}$	upper diagnostic range output voltage		[3]	96	-	100	$\%V_{DD}$
$V_{O(ldr)}$	lower diagnostic range output voltage		[3]	0	-	4	$\%V_{DD}$
$V_{(CL)u}$	upper clamping voltage		[4]	40	-	95	$\%V_{DD}$
$V_{(CL)l}$	lower clamping voltage		[4]	5	-	30.5	$\%V_{DD}$
$\Delta V_{(CL)}$	clamping voltage variation	deviation from programmed value		−0.3	-	+0.3	$\%V_{DD}$
I_O	output current	normal operation mode; operating as sink or source		-	-	2	mA
$V_{n(o)(RMS)}$	RMS output noise voltage	equivalent power noise	[5]	-	0.4	2.5	mV
$\Delta\phi_{lin}$	linearity error	temperature range −40 °C to +160 °C	[5][6]	−1.2	-	+1.2	deg
		temperature range −40 °C to +140 °C	[5][6]	−1	-	+1	deg
$\Delta\phi_{temp}$	temperature drift error	temperature range −40 °C to +160 °C	[1][5][6][7]	-	-	0.8	deg
		temperature range −40 °C to +140 °C	[1][5][6][7]	-	-	0.65	deg

Table 11. System performance *…continued*
Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
$\Delta\phi_{temp \mid RT}$	temperature drift error at room temperature	temperature range −40 °C to +160 °C	[6][7][8]	-	-	0.65	deg
		temperature range −40 °C to +140 °C	[6][7][8]	-	-	0.55	deg
$\Delta\phi_{hys}$	hysteresis error	referred to input	[5][6]	-	-	0.09	deg
$\Delta\phi_{\mu lin}$	microlinearity error	referred to input	[5][6]	−0.1	-	+0.1	deg
$\Delta\phi_{ang}$	angular error	temperature range −40 °C to +160 °C	[5][6][9]	−1.35	-	+1.35	deg
		temperature range −40 °C to +140 °C	[5][6][9]	−1.1	-	+1.1	deg
m_{ang}	slope of angular error		[5][6][9]	-	-	0.04	deg/deg
$Z_{O(pl)}$	power-loss output impedance	impedance to remaining supply line in case of lost supply voltage or lost ground		-	-	210	Ω

[1] At a nominal output voltage between 5 %V_{DD} and 95 %V_{DD} and a maximum angle of α_{max} = 180°.

[2] In steps of resolution < 0.022°.

[3] Activation is dependent on the programmed diagnostic mode.

[4] In steps of 0.02 %V_{DD}.

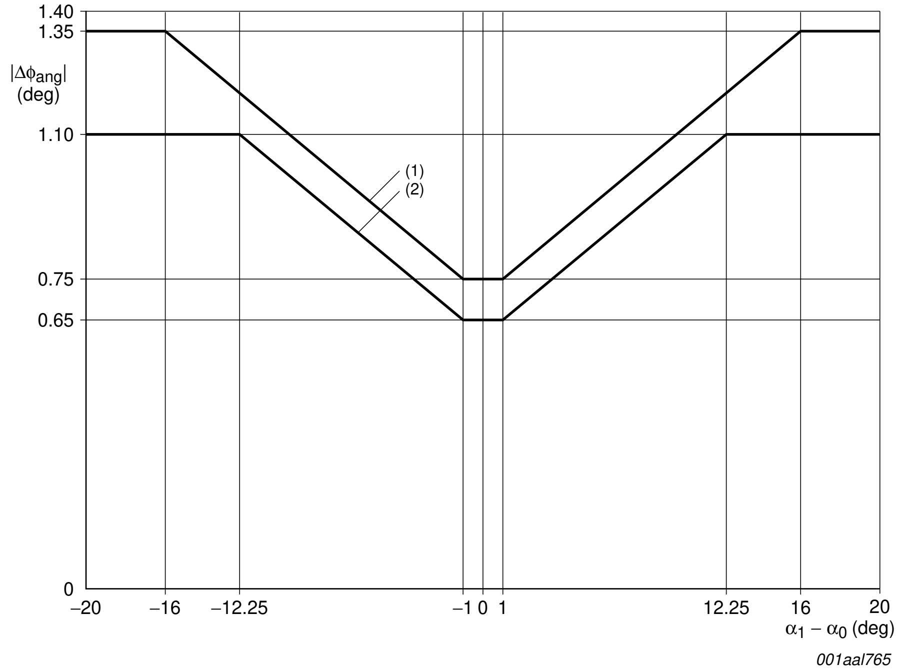
[5] At a low-pass filtered analog output with a cut-off frequency of 0.7 kHz.

[6] Definition of errors is given in Section 12.

[7] Based on a 3σ standard deviation.

[8] Room temperature is given for an ambient temperature of 25 °C.

[9] Graph of angular error is shown in Figure 5.



(1) −40 °C to +160 °C.

(2) −40 °C to +140 °C.

Fig 5. Envelope curve for the magnitude of angular error

Table 12. Dynamics

Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
t_{on}	turn-on time	until first valid result	[1]	-	-	5	ms
f_{upd}	update frequency			2	3.125	-	kHz
t_s	settling time	after an ideal mechanical angle step of 45°, until 90 % of the final value is reached; C_L = 5 nF		-	-	1.8	ms
$t_{cmd(ent)}$	enter command mode time	after power on		16	-	26	ms

[1] After reaching the power-on threshold voltage.

Table 13. Digital interface

Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{IH}	HIGH-level input voltage		80	-	-	$\%V_{DD}$
V_{IL}	LOW-level input voltage		-	-	20	$\%V_{DD}$
V_{OH}	HIGH-level output voltage	I_O = 2 mA	80	-	-	$\%V_{DD}$
V_{OL}	LOW-level output voltage	I_O = 2 mA	-	-	20	$\%V_{DD}$
I_{od}	overdrive current	absolute value for overdriving the output buffer	-	-	20	mA
t_{start}	start time	LOW level before rising edge	5	-	-	µs

Table 13. Digital interface *...continued*

Characteristics are valid for the operating conditions, as specified in Section 9.

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
t_{stop}	stop time	HIGH level before falling edge	5	-	-	μs
T_{bit}	bit period	minimum period may be limited by the load capacitance	10	-	100	μs
ΔT_{bit}	bit period deviation	deviation between received clock and sent clock	$0.8T_{bit}$	$1T_{bit}$	$1.2T_{bit}$	s
t_{w0}	pulse width 0		$0.175T_{bit}$	$0.25T_{bit}$	$0.375T_{bit}$	s
t_{w1}	pulse width 1		$0.625T_{bit}$	$0.75T_{bit}$	$0.825T_{bit}$	s
t_{to}	time-out time	digital communication reset guaranteed after maximum t_{to}	-	-	220	μs
$t_{tko(slv)}$	slave takeover time	duration of LOW level for slave takeover	1	-	5	μs
$t_{tko(mas)}$	master takeover time	duration of LOW level for master takeover	$0T_{bit}$	-	$0.5T_{bit}$	s
t_{prog}	programming time	for a single EEPROM address	20	-	-	ms
t_{cp}	charge pump time	waiting time after enabling the EEPROM charge pump clock	1	-	-	ms

12. Definition of errors

12.1 General

Angular measurement errors by the KMA199 result from linearity errors, temperature drift errors and hysteresis errors. Figure 6 shows the output signal of an ideal sensor, where the measured angle ϕ_{meas} corresponds ideally to the magnetic field angle α. This curve will further be denoted as angle reference line $\phi_{ref}(\alpha)$ with a slope of 0.5 $\%V_{DD}$/deg.

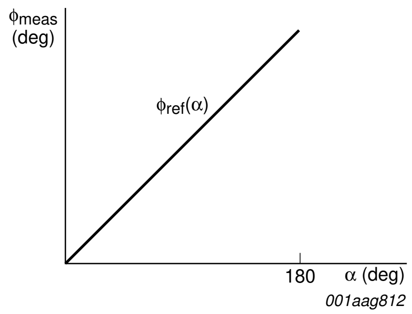


Fig 6. Definition of the reference line

The angular range is set to α_{max} = 180° and the clamping voltages are programmed to $V_{(CL)l}$ = 5 $\%V_{DD}$ and $V_{(CL)u}$ = 95 $\%V_{DD}$ for a valid definition of errors.

12.2 Hysteresis error

The hysteresis error $\Delta\phi_{hys}$ is defined as the maximum difference between the angles, given by the device output when performing a positive (clockwise) rotation and negative (counter clockwise) rotation over an angular range of 180°, measured at a constant temperature.

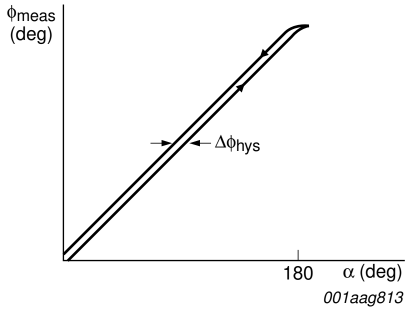


Fig 7. Definition of the hysteresis error

Equation 1 gives the mathematical description for the hysteresis value $\Delta\phi_{hys}$:

$$\Delta\phi_{hys}(\alpha) = \left|\phi_{meas}(\alpha \rightarrow 180^{\circ}) - \phi_{meas}(\alpha \rightarrow 0^{\circ})\right| \quad (1)$$

12.3 Linearity error

The KMA199 output signal deviation from a best straight line ϕ_{BSL}, with the same slope as the reference line, is defined as linearity error. The magnetic field angle is varied at fixed temperatures for measurement of this linearity error. The output signal deviation from the best straight line at the given temperature is the linearity error $\Delta\phi_{lin}$. It is a function of the magnetic field angle α and the temperature of the device T_{amb}.

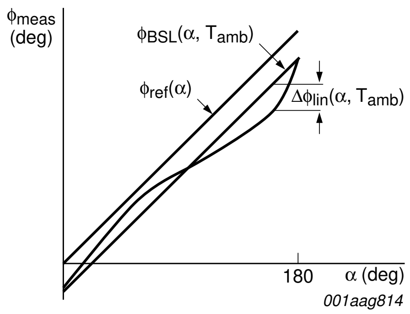


Fig 8. Definition of the linearity error

12.4 Microlinearity error

The microlinearity error $\Delta\phi_{\mu lin}$ is the device output deviation from 1°, if the magnetic field angle α is changed by $\Delta\alpha$ = 1°.

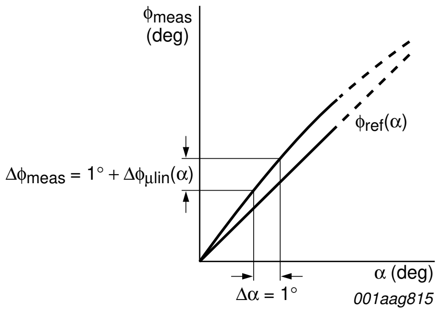


Fig 9. Definition of the microlinearity error

12.5 Temperature drift error

The temperature drift $\Delta\phi_{temp}$ is defined as the envelope over the deviation of the angle versus the temperature range. It is considered as the pure thermal effect.

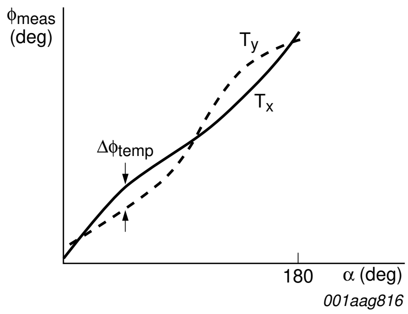


Fig 10. Definition of the temperature drift error

Equation 2 gives the mathematical description for temperature drift value $\Delta\phi_{temp}$:

$$\Delta\phi_{temp}(\alpha) = \left|\phi_{meas}(\alpha, T_x) - \phi_{meas}(\alpha, T_y)\right| \quad (2)$$

with:

T_x: temperature for maximum ϕ_{meas} at angle α

T_y: temperature for minimum ϕ_{meas} at angle α

The deviation from the value at room temperature $\Delta\phi_{temp|RT}$ describes the temperature drift of the angle, compared to the value, which the sensor provides at room temperature:

$$\Delta\phi_{temp|RT}(\alpha, T_{amb}) = |\phi_{meas}(\alpha, T_{amb}) - \phi_{meas}(\alpha, T_{RT})| \quad (3)$$

with:

T_{RT}: room temperature (25 °C)

12.6 Angular error

The angular error $\Delta\phi_{ang}$ is the error of angle difference measured by the sensor, if the mechanical angle deviates from α_0 to α_1. Here α_0 and α_1 are arbitrary angles within the angular range. The angle measurement at α_0 is the initially programmed reference angle, programmed by the customer at room temperature and zero hour upon production. The angle measurement at α_1 is made at any temperature within the ambient temperature range:

$$\Delta\phi_{ang} = (\phi_{meas}(\alpha_1, T_{amb}) - \phi_{meas}(\alpha_0, T_{RT})) - (\alpha_1 - \alpha_0) \quad (4)$$

with:

α_0, α_1: arbitrary mechanical angles within the angular range

$\phi_{meas}(\alpha_0, T_{RT})$: programmed angle at α_0, T_{RT} = 25 °C and zero hour upon production

$\phi_{meas}(\alpha_1, T_{amb})$: angle measured by the sensor at α_1 and any temperature within T_{amb}

This error comprises non-linearity and temperature drift related to the room temperature.

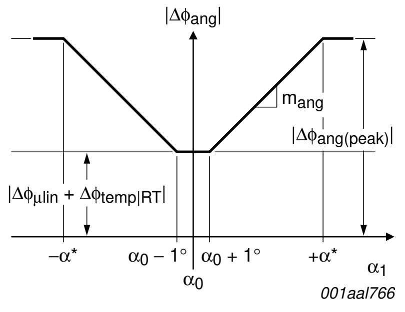


Fig 11. Definition of the angular error

Figure 11 shows the envelope curve for the magnitude of angular error $|\Delta\phi_{ang}|$ versus α_1 for all angles α_0 and all temperatures T_{amb} within the ambient temperature range. $|\Delta\phi_{ang}|$ has its minimum, if α_1 is in the range of ±1° around α_0. Here only the microlinearity error $\Delta\phi_{\mu lin}$ and the temperature drift related to the room temperature $|\Delta\phi_{temp|RT}|$ occurs. If α_1 deviates from α_0 by more than 1° in either direction, $|\Delta\phi_{ang}|$ can increase with a gradient defined by slope m_{ang}.

Angular error can be expressed by Equation 5 to Equation 8:

for $|\alpha_1 - \alpha_0| \leq 1°$

$$|\Delta\phi_{ang}| = |\Delta\phi_{\mu lin} + \Delta\phi_{temp|RT}| \quad (5)$$

for $1° < |\alpha_1 - \alpha_0| < \alpha^*$

$$|\Delta\phi_{ang}| = |\Delta\phi_{\mu lin} + \Delta\phi_{temp|RT}| + m_{ang} \times (|\alpha_1 - \alpha_0| - 1°) \quad (6)$$

for $|\alpha_1 - \alpha_0| \geq \alpha^*$

$$|\Delta\phi_{ang}| = \sqrt{(\Delta\phi_{lin})^2 + (\Delta\phi_{temp|RT})^2} \quad (7)$$

with:

$$\alpha^* = \frac{|\Delta\phi_{\mathrm{ang(peak)}}| - |\Delta\phi_{\mu lin} + \Delta\phi_{temp|RT}|}{m_{ang}} + \alpha_0 + 1° \quad (8)$$

13. Programming

13.1 General description

The KMA199 provides an OWI to enable programming of the device which uses pin OUT/DATA bidirectionally.

In general the device runs in analog output mode, the normal operating mode. This mode is configured by the embedded programming data and is started after a power-on reset once time t_{on} has elapsed. In this mode, the magnetic field angle is converted into the corresponding output voltage.

Command mode has to be entered to enable programming. In this mode, the customer can adjust all required parameters (for example zero angle and angular range) to meet the application requirements. After enabling the internal charge pump and waiting for t_{cp} the data is stored in the EEPROM. After changing the contents of the EEPROM, the checksum must be recalculated and written (see Section 13.4).

In order to enter the command mode, a specific command sequence must be send after a power-on reset and during the time slot $t_{cmd(ent)}$. The external source used to send the command sequence must overdrive the output buffer of the KMA199 ($I > I_{od}$).

During communication, the KMA199 is always the slave and the external programming hardware is the master. Figure 12 illustrates the structure of the OWI data format.

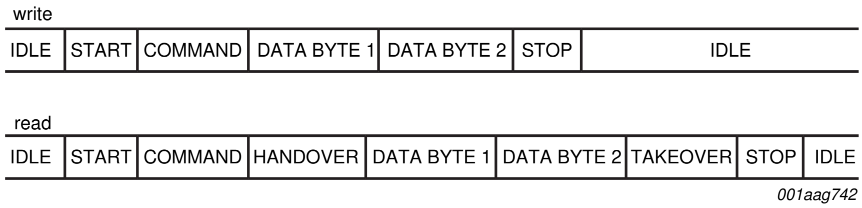


Fig 12. OWI data format

The master provides the start condition, which is a rising edge after a LOW level. Then a command byte which can be either a read or a write command is send. Depending on the command, the master or the slave has to send the data immediately after the command sequence. In the case of a read command, an additional handover or takeover bit is inserted before and after the data bytes. Each communication must be closed with a stop condition driven by the master. If the slave does not receive a rising edge for a time longer than t_{to}, a time-out condition occurs. The bus is reset to the idle state and waits for a start condition and a new command. This can be used to synchronize the device regardless of the previous state.

All communication is based on this structure (see Figure 12), even for entering the command mode. In this case a special write command is required, followed by the command sequence (two data bytes). The customer can access the EEPROM, CTRL1, TESTCTRL0 and SIGNATURE registers (described in Section 13.5). Only a power-on reset will leave the command mode. A more detailed description of the programming is given in the next sections.

13.2 Timing characteristics

As described in the previous section, a start and stop condition is necessary for communication. The LOW-level duration before the rising edge of the start condition is defined as t_{start}. The HIGH-level duration after the rising edge of the stop condition is defined as t_{stop}. These parameters, together with all other timing characteristics are shown in Table 13.

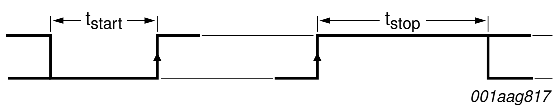


Fig 13. OWI start and stop condition

Figure 14 shows the coding of a single bit with a HIGH level of V_{IH} and a LOW level of V_{IL}. Here the pulse width t_1 or t_0 represents a logic 1 or a logic 0 of a full bit period T_{bit}, respectively.

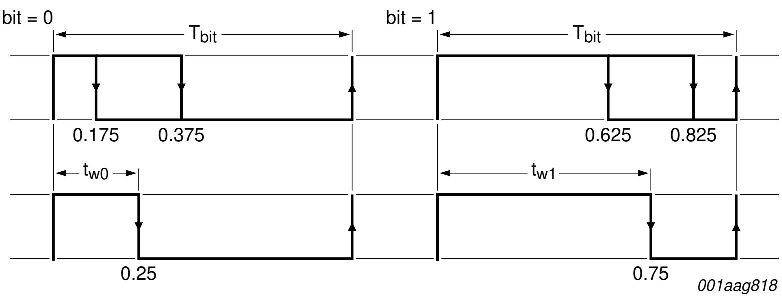


Fig 14. OWI timing

13.3 Sending and receiving data

The master has to control the communication during sending or receiving data. The command byte defines the region, address and type of command requested by the master. In case of a read command, an additional handover or takeover bit must be inserted before and after the two data bytes (see Figure 12). However the OWI is a serial data transmission, whereas the Most Significant Byte (MSB) must be send at first.

Table 14. Format of a command byte

7	6	5	4	3	2	1	0
CMD7	CMD6	CMD5	CMD4	CMD3	CMD2	CMD1	CMD0

Table 15. Command byte bit description

Bit	Symbol	Description
7 to 5	CMD[7:5]	region bits
		000 = 16-bit EEPROM
		001 to 011 = reserved
		100 = 16-bit register
		101 to 111 = reserved
4 to 1	CMD[4:1]	address bits
0	CMD0	read/write
		0 = write
		1 = read

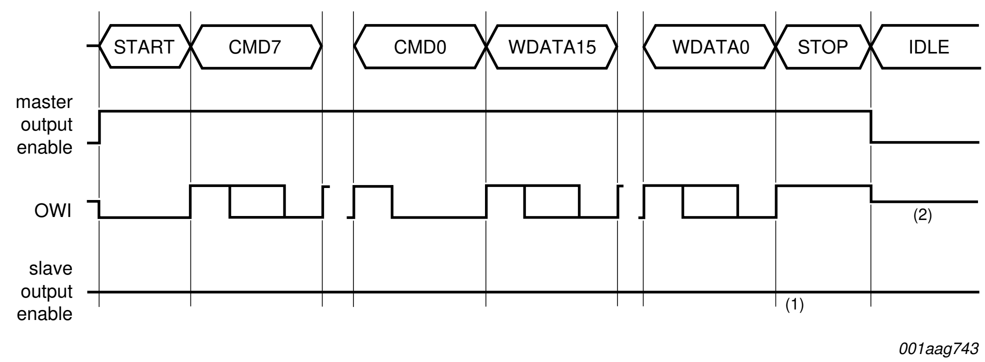
A more detailed description of all customer accessible registers is given in Section 13.5. Both default value and the complete command including the address and write or read request are also listed.

13.3.1 Write access

To write data to the EEPROM, the internal charge pump must be enabled by setting the bits EEP_CP_CLOCK_EN and EEP_WRITE_EN and waiting for t_{cp}. The following procedure must be performed:

- Start condition: The master drives a rising edge after a LOW level
- Command: The master sends a write command (CMD0 = 0)
- Data: The master sends two data bytes
- Stop condition: The master drives a rising edge after a LOW level

Figure 15 shows the write access of the digital interface. The signal OWI represents the data on the bus from the master or slave. The signals master output enable and slave output enable just symbolize if the master or the slave output is enabled or disabled, respectively.



(1) Missing rising edges generate a time-out condition and the written data is ignored.

(2) If the master does not drive the bus, the bus is defined by the bus-pull.

Fig 15. OWI write access

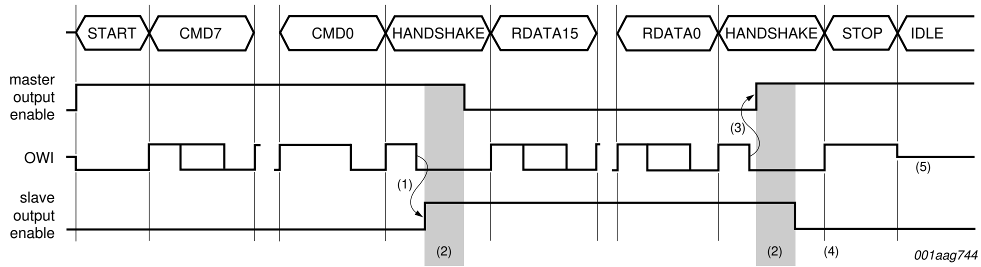
Note: As already mentioned in Section 13.1, the command mode has to be entered using the write procedure. If command mode is not entered, digital communication is not possible and the sensor operates in normal operating mode. After changing an address, the time t_{prog} must elapse before changing another address. Finally the checksum must be recalculated and written, after changing the contents of the EEPROM (see Section 13.4).

13.3.2 Read access

To read data from the sensor, the following procedure must be performed:

- Start condition: The master drives a rising edge after a LOW level
- Command: The master sends a read command (CMD0 = 1)
- Handover: The master sends a handover bit, that is a logic 0 and disables the output after a three-quarter bit period
- Takeover: The slave drives a LOW level after the falling edge for $t_{tko(slv)}$
- Data: The slave sends two data bytes
- Handover: The slave sends a handover bit, that is a logic 0 and disables the output after a three-quarter bit period
- Takeover: The master drives a LOW level after the falling edge for $t_{tko(mas)}$
- Stop condition: The master drives a rising edge after a LOW level

Figure 16 shows the read access of the digital interface. The signal OWI represents the data on the bus from the master or slave. The signals master output enable and slave output enable just symbolize if the master or the slave output is enabled or disabled, respectively.



(1) Duration of LOW level for slave takeover $t_{tko(slv)}$.

(2) There is an overlap in the output enables of master and slave, because both drive a LOW level. However this ensures the independency from having a pull-up or pull-down on the bus. In addition it improves the ElectroMagnetic Compatibility (EMC) robustness, because all levels are actively driven.

(3) Duration of LOW level for master takeover $t_{tko(mas)}$.

(4) If the master does not take over and a pull-up exists, the stop condition is generated by the pull-up. Otherwise a time-out is generated if there is a pull-down and the slave waits for a rising edge as start condition.

(5) If the master does not drive the bus, the bus is defined by the bus-pull.

Fig 16. OWI read access

13.3.3 Entering the command mode

After a power-on reset, the sensor provides a time slot $t_{cmd(ent)}$ for entering the command mode. A specific command sequence has to be send (see Figure 17). If command mode is not entered, the sensor starts in the normal operating mode. However the signature can be written by the master, if the sensor switches to diagnostic mode.

During the command mode sequence, the analog output is enabled. The external programming hardware has to overdrive the output with the current I_{od}. If command mode is activated, the analog output is disabled and pin OUT/DATA operates as a digital interface.

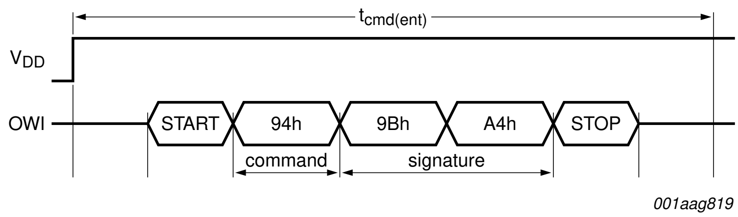


Fig 17. OWI command mode procedure

13.4 Cyclic redundancy check

As already mentioned in Section 7, there is an 8-bit checksum for the EEPROM data. To calculate this value, the CRC needs to be generated with the MSB of the EEPROM data word at first over all corresponding addresses in increasing order.

All addresses from 0h to Fh have to be read out for calculating the checksum. The Least Significant Byte (LSB) of address Fh which contains the previous checksum must be overwritten with 0h before the calculation can be started.

Finally, the internal charge pump has to be enabled for programming by setting the bits EEP_CP_CLOCK_EN and EEP_WRITE_EN (see Table 16) and waiting for t_{cp}.

The generator polynomial for the calculation of the checksum is:

$$G(x) = x^8 + x^2 + x + 1 \tag{9}$$

With a start value of FFh and the data bits are XOR at the x^8 point.

13.4.1 Software example in C

```c
#include <stdio.h.>

// calc_crc accepts unsigned 16-bit data in data
int calc_crc(int crc, unsigned int data)
{
      const int gpoly = 0x107; // generator polynomial
      int i;                   //index variable
      for (i = 15; i >= 0; i--)
      {
            crc <<= 1;         //shift left
            crc |= (int) ((data & (1u<<i))>>i);
            // XOR of with generator polynomial when MSB(9) = HIGH
            if (crc & 0x100) crc ^= gpoly;
      }
      return crc;
}
int main(void)
{
      int crc, crc_res, i;
      // 8 LSB are CRC field filled with 0
      unsigned int data_seq[] = {0x1111, 0x2222, 0x3333, 0x4444,
                                 0x5555, 0x6666, 0x7777, 0x8888,
                                 0x9999, 0xAAAA, 0xBBBB, 0xCCCC,
                                 0xDDDD, 0xEEEE, 0xFFFF, 0x4200};
      // calculate checksum over all data
      crc = 0xFF;                // start value of crc register
      printf(“Address\tValue\n”);
      for (i = 0; i <= 15; i++)
            {
            printf(“0x%1X\t0x%04X\n”, i, data_seq[i]);
            crc = calc_crc(crc, data_seq[i]);
            }
      crc_res = crc;             // crc_res = 0x6F
      printf(“\nChecksum\n0x%02X\n”, crc_res);
      // check procedure for above data sequence
      crc = 0xFF;
      for (i = 0; i <= 14; i++)
            crc = calc_crc(crc, data_seq[i]);
      // last word gets crc inserted
      crc = calc_crc(crc, data_seq[i] | crc_res);
      printf(“\nCheck procedure for data sequence: must be 0x00 is 0x%02X.\n”,crc);
      return 1;
}
```

The checksum of this data sequence is 6Fh.

13.5 Registers

13.5.1 Command registers

To enter the command mode, the signature given in Table 16 must be written using the OWI into the specific register. This must be done as described in Section 13.3.3, with a write command, followed by the signature, but after a power-on reset and not later than $t_{cmd(ent)}$.

Table 16. Command registers

Command write/read	Register	Bit	Access	Field	Description
82h/83h	CTRL1	15	R	IN_DIAG_MODE	shows if there is a diagnostic condition present; this bit is not affected by the setting of the register field FORCE_DIAG_OFF
		14	R/W	FORCE_DIAG_OFF	force diagnostic mode off; default: 0b
		13	-	-	reserved
		12	R	LOW_VOLTAGE_DET	low voltage condition detected
		11	R/W	EEP_CP_CLOCK_EN	charge pump clock on (must be set after setting EEPROM write enable signal for writing to EEPROM); default: 0b
		10 and 9	-	-	reserved
		8	R	EEP_ERR_CORRECT	EDC: EEPROM error has been corrected; updated every EEPROM readout and remains set once set
		7	R	EEP_UNCORR_ERR	EDC: EEPROM uncorrectable error has been detected; updated every EEPROM readout and remains set once set
		6	R	MAGNET_LOSS_DET	magnet-loss detected; bit remains set even if the condition disappears; for this detection which leads to diagnostic mode, the magnet-loss detection must be enabled
		5	-	-	reserved
		4	R	CRC_BAD	CRC check has failed (checked during start-up)
		3 to 0	-	-	reserved
94h/-	SIGNATURE	15 to 0	W	SIGNATURE	write signature 9BA4h within $t_{cmd(ent)}$ to enter command mode; see Section 13.3.3 for more details
96h/97h	TESTCTRL0	15 to 12	-	-	reserved
		11	W	EEP_WRITE_EN	EEPROM write enable signal (must be set before writing to EEPROM) **0605h** — disabled (default) **0E05h** — enabled
		10 to 0	-	-	reserved

13.5.2 EEPROM registers

The device includes several internal registers which are used for customization and identification.

The initial signature allows read access to all areas but only write access to customer registers. Write accesses to reserved areas are ignored. Since these registers are implemented as EEPROM cells, writing to the registers needs a specific time t_{prog} after each write access to complete.

As there is no check for the programming time, the user must make sure no other accesses to the EEPROM are made during the programming cycle. The EEPROM must not be addressed during the time t_{prog}.

Note: Before data can be stored in the EEPROM, the internal charge pump has to be switched on for the programming duration by setting register CTRL1, bit 11 EEP_CP_CLOCK_EN and register TESTCTRL0, bit 11 EEP_WRITE_EN. All register addresses have to be read out for calculating the checksum. However, some register addresses are reserved for calibration.

Table 17. EEPROM registers

Address	Command write/read	Register	Bit	Description	Default MSB/LSB
0h	-/01h	reserved	-	addresses are reserved for calibration purposes **Note**: These addresses have to be read out for calculating the checksum.	[1]
1h	-/03h				
2h	-/05h				
3h	-/07h				
4h	-/09h				
5h	-/0Bh				
6h	-/0Dh				
7h	0Eh/0Fh	ZERO_ANGLE	15 to 0	mechanical zero degree position	00h/00h
8h	10h/11h	MAGNET_LOSS	15 to 0	magnet-loss detection **0000h** — disabled **004Fh** — enabled	00h/00h
9h	12h/13h	ANG_RNG_MULT_LSB	15 to 3	least significant bits of the angular range multiplicator	20h/00h
			2 to 0	undefined[2]	
Ah	14h/15h	CLAMP_LO	15 to 13	undefined[2]	01h/00h
			12 to 0	lower clamping level output voltage	
Bh	16h/17h	CLAMP_HI	15 to 13	undefined[2]	12h/FFh
			12 to 0	upper clamping level output voltage	
Ch	18h/19h	ID_LO	15 to 0	lower 16 bits of identification code	00h/00h
Dh	1Ah/1Bh	ID_HI	15 to 0	upper 16 bits of identification code	00h/00h
Eh	1Ch/1Dh	CLAMP_SW_ANGLE	15 to 6	when angle is bigger than CLAMP_SW_ANGLE the output switches to CLAMP_LO for a positive slope	FFh/C1h
		ANG_RNG_MULT_MSB	5 to 0	most significant bits of the angular range multiplicator	

Table 17. EEPROM registers *…continued*

Address	Command write/read	Register	Bit	Description	Default MSB/LSB
Fh	1Eh/1Fh	EEP_CTRL_CUST	15 and 14	undefined[2]	0Ch/[1]
			13 and 12	DIAGNOSTIC_LEVEL; diagnostic level behavior of the analog output **00b** — active LOW (in lower diagnostic range) with driver strength of the analog output **01b** — active HIGH (in upper diagnostic range) with driver strength of the analog output **10b** — reserved **11b** — reserved	
			11 and 10	reserved; may not be changed	
			9	undefined[2]	
			8	SLOPE_DIR; slope of analog output **0b** — rising (not inverted) **1b** — falling (inverted)	
			7 to 0	CRC; checksum over all data (see Section 13.4)	

[1] Variable and individual for each device.

[2] Undefined; must be written as zero for default.

Table 18. ZERO_ANGLE - mechanical zero degree position (address 7h) bit allocation

Data format: unsigned fixed point; resolution: 2^{-16}.

Bit	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Value	2^{-1}	2^{-2}	2^{-3}	2^{-4}	2^{-5}	2^{-6}	2^{-7}	2^{-8}	2^{-9}	2^{-10}	2^{-11}	2^{-12}	2^{-13}	2^{-14}	2^{-15}	2^{-16}

Mechanical angular range 0000h = 0° to FFFFh = 180° – 1 LSB

Examples:

- Mechanical zero angle 0° = 0000h
- Mechanical zero angle 10° = 0E38h
- Mechanical zero angle 45° = 4000h

Table 19. ANG_RNG_MULT_LSB - least significant bits of angular range multiplicator (address 9h) bit allocation

Data format: unsigned fixed point; resolution: 2^{-14}.

Bit	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Value	2^{-2}	2^{-3}	2^{-4}	2^{-5}	2^{-6}	2^{-7}	2^{-8}	2^{-9}	2^{-10}	2^{-11}	2^{-12}	2^{-13}	2^{-14}	U[1]	U[1]	U[1]

[1] Undefined; must be written as zero for default and may return any value when read.

$$ANG\_RNG\_MULT = \frac{CLAMP\_HI - CLAMP\_LO}{8192} \times \frac{180°}{ANGULAR\_RANGE} \quad (10)$$