Rotationally Symmetrical Speed Sensor with Detection of Direction of Rotation

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Abstract

In many applications with magnetic field-based speed sensors and passive target wheels, the rotatability of the sensor due to rotational symmetry is an important application criterion; likewise, tooth mapping independent of the air gap and, increasingly, detection of the direction of rotation are frequently required. The rotational symmetry can preferably be achieved by a single sensor element on the axis of rotation. For the detection of the direction of rotation, an asymmetrical shape of the teeth of the sensor wheel is then required. In the concept proposed here, a tooth mapping that is almost independent of the air gap is also achieved - at least for one tooth edge.

1 Rotational speed sensors

In many applications of rotational speed sensors with soft magnetic (passive) target wheels, the most accurate possible representation of the mechanical edges is desired (e.g. for camshaft or crankshaft speed sensors [7]) - this means that the electrical edges always produce the same tooth mapping, as far as possible independent of the air gap AG and other conditions. It is also desirable to detect the direction of rotation, which is basically impossible with a rotationally symmetrical design (TIM: **T**wist **i**nsensitive **m**ounting) with only one sensor element and a "regularly shaped" target wheel. Furthermore, **t**rue **p**ower **o**n (TPO) functionality can be achieved with one sensor element and the so-called absolute field method - i.e. immediately after switching on the supply voltage, the sensor can distinguish between tooth and notch.

The sensor (see **Figure 1**) usually contains at least one permanent magnet and a sensing element (Hall or XMR) which detects the change in magnetic flux density B, since B depends on whether there is a tooth (then: $B = B_{MAX}$ with air gap AG as minimum distance between sensor and tooth) or a notch (then: $B = B_{MIN}$) in front of the sensor. The change in flux density ΔB can then be calculated by: $\Delta B = B_{MAX} - B_{MIN}$. The signal quality is determined by the relative change in $\Delta B/B_{MIN}$.

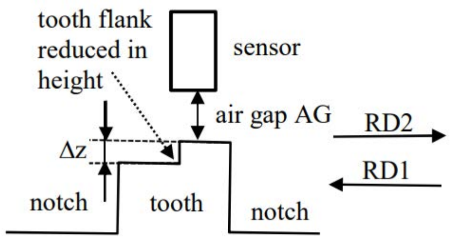

Figure 1 Principle arrangement of sensor and target wheel (RD1/2: Rotational Direction 1/2) with asymmetrical tooth

As shown in **Figure 2**, the change in magnetic flux density ΔB - and also the relative change $\Delta B/B_{MIN}$ - is strongly dependent on the air gap AG. From this it is clear that precise tooth mapping is not possible with one fixed threshold due to the fact that the absolute values of the magnetic flux density B strongly depend on the air gap AG.
The exact values of the magnetic flux density B (or $\Delta B/B_{MIN}$) as a function of the air gap AG also depend on the design of the magnetic circuit. However, the behaviour is also quite similar for different magnetic circuits. For this research data from different sensors [1], [4], [5], [6] were also used, which always led to similar results.

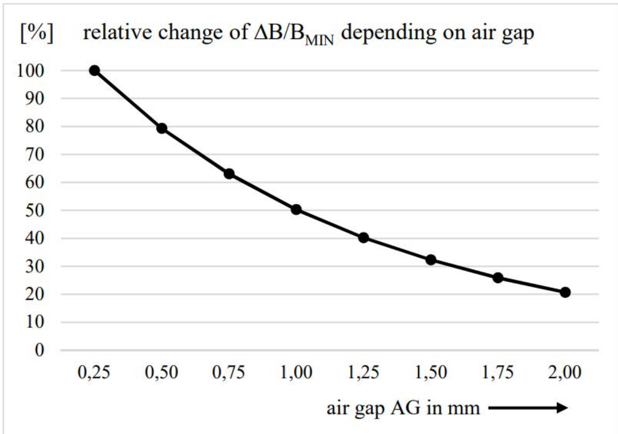

Figure 2 Normalised change of $\Delta B/B_{MIN}$ (100 % at air gap AG = 0.25 mm)

2 Algorithm for precise tooth mapping

In order to achieve a precise tooth mapping that is not dependent on the air gap AG, an algorithm is proposed that is based on the evaluation of the output signal of the magnetic field sensor (Hall or XMR); for this purpose, the maximum and minimum of the magnetic flux density B is recorded

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over at least one pair of tooth/notch; these values are then used to determine the optimum switching threshold, which is approximately 70 % of the maximum possible change in the magnetic flux density B_{MAX}. In this way, it can at least be achieved that the edges of a “regular shaped” tooth correspond accurately with the electrical digital output signals; this appears almost independent of the air gap AG as described in [1] or [2].

2.1 Rectangular target wheel with asymmetrical tooth design

In the case of a target wheel with asymmetrical tooth design (with different tooth height Δz; see Figure 1), the air gap AG will be locally increased by Δz. This leads to a relatively constant change in the relative magnetic flux density change $\Delta B/B_{MIN}$ for different air gaps AG, as indicated in **Figure 3**; Δz means an increase of the air gap AG. This means that when the edge height is changed by Δz, $\Delta B/B_{MIN}$ changes only slightly over the entire air gap range.
This also applies in a similar way to other magnetic circuits [1], [4], [5], [6], whereby the values for the change in magnetic flux density B may be different. The normalised values $\Delta B/B_{MIN\_NORM}$ and the behaviour over the air gap range are similar.

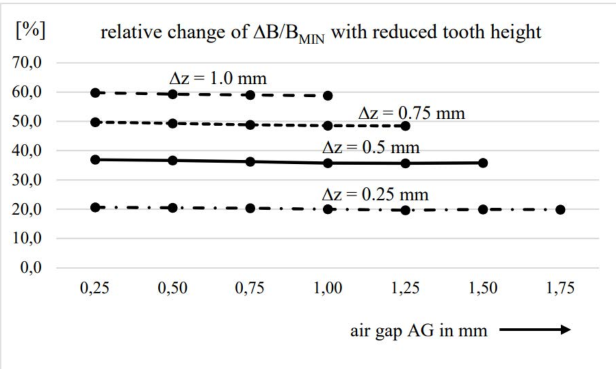

Figure 3 Relative change of $\Delta B/B_{MIN}$ for a given air gap AG (100 % corresponds to the maximum tooth height, tooth as depicted in Figure 1)

With a “step-shaped” tooth form, for example, (see Figure 1, reduced tooth height Δz of about 0.75 mm) there is a corresponding change in the magnetic flux density B or the (normalised) change in the relative flux density $\Delta B/B_{MIN\_NORM}$ by about 50 % due to the change Δz of the air gap AG as depicted in Figure 3; the normalised value of $\Delta B/B_{MIN\_NORM}$ is represented in **Figure 4** for the direction of rotation RD1. With the two switching thresholds A (ON, 70 % of the maximum of the normalised value of $\Delta B/B_{MIN\_NORM}$) and B (OFF, 30 % of the normalised value of the maximum of $\Delta B/B_{MIN\_NORM}$), a different duty cycle results depending on the direction of rotation (RD1 or RD2), as can be seen from a comparison of the digital output signals of the two **Figures** 4 and **5**.
Due to the normalised representation and evaluation of $\Delta B/B_{MIN\_NORM}$, the curves shown in Figures 4 and 5 are very similar for almost the entire air gap range, since an optimum tooth mapping results at a switching threshold of 70 %, which is almost independent of the air gap AG.

Due to the relatively constant reduction of $\Delta B/B_{MIN}$ with a smaller tooth edge (change of the tooth height Δz leads to an increase of the airgap AG; see Figure 3), which is almost independent of the air gap AG, a duty cycle dependent on the direction of rotation can thus be achieved, whereby an electrical edge of the digital output signal with the switching threshold ON (corresponds to 70 % here) precisely maps the mechanical tooth edge. This means that here the rising edge of the digital output signal (switching threshold A, ON, 70%) can be used to precisely determine the speed.

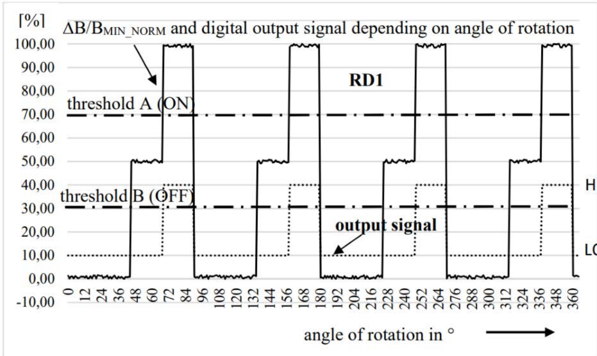

Figure 4 Normalised change of $\Delta B/B_{MIN\_NORM}$ for a given air gap AG; **RD1** and tooth as depicted in Figure 1

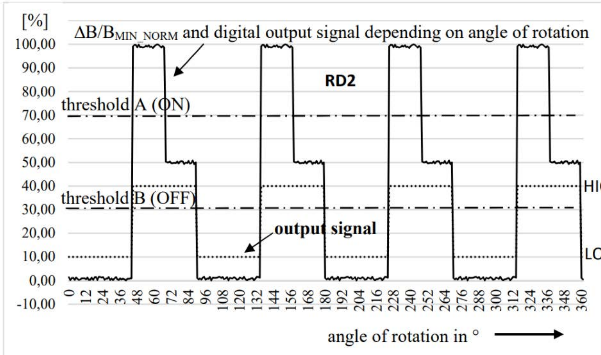

Figure 5 Normalised change of $\Delta B/B_{MIN\_NORM}$ for a given air gap AG; **RD2** and tooth as depicted in Figure 1

2.2 Triangular target wheel with asymmetrical tooth

Similar statements also apply to other asymmetrical target wheels. As another example a triangular asymmetrical soft magnetic target wheel is shown in **Figure 6**. The (simulated) normalised relative change of the magnetic flux density $\Delta B/B_{MIN\_NORM}$ in direction of rotation 1 (RD1) is depicted In **Figure 7**; with the switching thresholds A (ON, 70 %) and B (OFF, 30 %), a different duty cycle of the digital output signal is obtained compared to direction of rotation 2 (RD2), as shown in **Figure 8**.

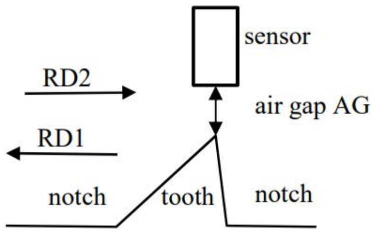

Figure 6 Principle arrangement of sensor and target wheel with asymmetrical tooth (RD: Rotational Direction)

Thus, the duty cycle of the digital output signal can be used to identify the direction of rotation; again, the tooth mapping at switching threshold A (ON, 70 %) is almost independent of the air gap AG.

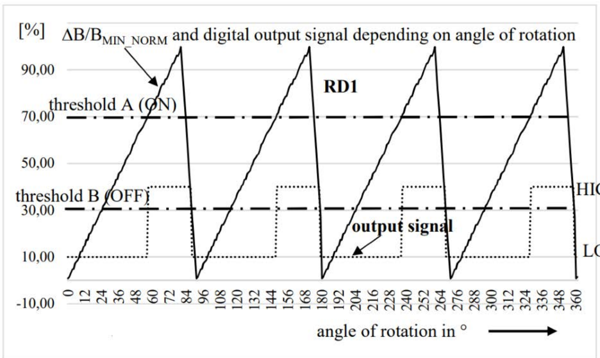

Figure 7 Normalised change of $\Delta B/B_{MIN\_NORM}$ for a given air gap AG; **RD1** and tooth as depicted in Figure 6

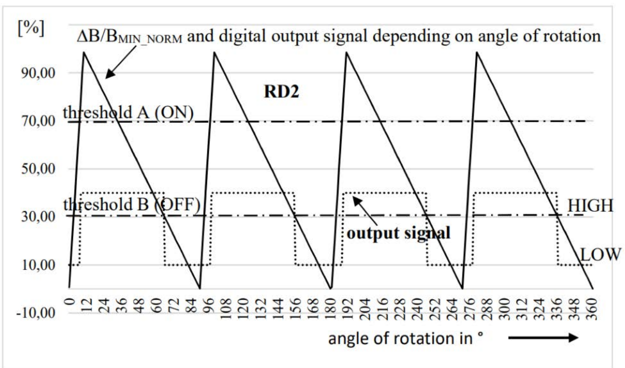

Figure 8 Normalised change of $\Delta B/B_{MIN\_NORM}$ for a given air gap AG; **RD2** and tooth as depicted in Figure 6

3 Summary

By means of an asymmetry of the teeth (for example, "contour stepped" tooth or asymmetrical triangle) a corresponding output signal is achieved, which by means of suitable switching thresholds A (ON, 70 % of $\Delta B/B_{MIN\_NORM}$) and B (OFF, 30 % of $\Delta B/B_{MIN\_NORM}$) allows a conclusion to be drawn about the direction of rotation (RD1 or RD2) on the basis of the different duty cycle. It can be seen that, for example, with a suitable choice of the "step" of the tooth, the output signal is almost independent of the air gap AG, so that the switching thresholds A and B of the digital output signal are independent of the air gap and can be determined on the basis of the normalisation of the change in the magnetic flux density B. Overall, with this concept - with little change in the teeth of the soft magnetic (so called passive) target wheel - a rotationally symmetrical sensor achieves precise tooth mapping of at least one edge for the speed and also detection of the direction of rotation; all this is valid according to simulation and available data also for different magnetic circuits for a large air gap range.

A more detailed description of the method will be published in [3].

4 Literature

[1] Patent WO 03/016921 A2, PCT/DE02/02631, Weltorganisation für geistiges Eigentum, 2003

[2] Offenlegungsschrift DE 10 2017 202 696 A1, Deutsches Patent- und Markenamt, München, 2017

[3] Gebrauchsmuster DE 20 2021 000 701.6, Deutsches Patent- und Markenamt, München, to be published in 2022

[4] Allegro Microsystems, Data sheet ATS128LSE, February 27, 2000

[5] Allegro Microsystems, Data sheet ATS651LSH, December 5, 2016

[6] Allegro Microsystems, Data sheet ATS692LSH, May, 2020

[7] Tille, T. (Hrsg.): Automobil-Sensorik 2, Kapitel 8, Springer-Verlag Berlin Heidelberg, 2018 (DOI 10.1007/978-3-662-56310-6_8)

