Mechanical mounting variation effects on magnetic speed sensor applications

Combining finite element methods and SystemC simulations to study the effects of mechanical tilts and offset on magnetic speed sensor applications

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***Abstract* — Magnetic speed sensors are used in automotive applications to sense the rotational speed of a target wheel. The environment they work in is harsh and safety requirements must be fulfilled. During the mechanical mounting process it is very difficult to have a perfect alignment between the sensor and wheel and some tilts can happen. Tilts in the sensor position could affect the sensor functionalities and the overall application. Performing measurements is expensive and time consuming, hence it would be highly beneficial to simulate the scenario. In this paper we study the effects of tilts on Infineon new generation wheel speed sensors TLE5046iC using the output of magnetic finite element analysis as the input for the SystemC sensor model. Simulating different tilting scenarios we examine what happens on the magnetic input field and on the sensor functionalities. The simulation procedure and the interpretation of results are automatized with Matlab scripts.**

Keywords—SystemC; finite element methods; simulation; magnetic speed sensors; tilt; modeling

I. INTRODUCTION

Magnetic wheel speed sensors are used to measure the rotational speed of the wheels and send this information to the Electronic Control Unit (ECU). The environment they work in is often harsh and safety requirements must be fulfilled to ensure the safety of the driver and of the other people on the road. The sensors are main component of Anti-lock Braking system (ABS). They are normally used for wheel speed detection in over molded module. During the mechanical mounting process it is very difficult to have a perfect alignment between the sensor and wheel and some tilts can happen in all the directions. Tilts in the sensor position could affect the sensor functionalities and the overall application. Indeed the magnetic field configuration applied to the sensor changes depending on the sensor rotation around the three axes. Performing measurements is expensive and time consuming, hence it would be highly beneficial to simulate the scenario to understand the effects on the sensors and on the overall application and find a general trend.

In this paper we study the effects of tilts on Infineon new generation wheel speed sensor TLE5046iC [1] as an example, using the output of magnetic finite element analysis as the input for the SystemC sensor model. In particular, using the Finite Element Method (FEM) we simulate a wheel speed sensing scenario, where a magnetic encoder rotates around an axis and the magnetic sensor mounted parallel to the wheel measures the magnetic field variation. The outputs of these simulations are then fed as an input to the SystemC sensor model, which describes the detailed behavior of the sensor. Simulating different tilting scenarios for different airgaps and mechanical offsets we examine what happens on the magnetic input field as well as on the sensor functionalities. In particular, we check if the sensor goes into calibrated mode, i.e. the sensor generates a new protocol when the magnetic field crosses the zero threshold, and works within the requirements. The simulation procedure and the interpretation of results are completely automatized with Matlab scripts. Figure 1 shows a diagram explaining the goal of this work.

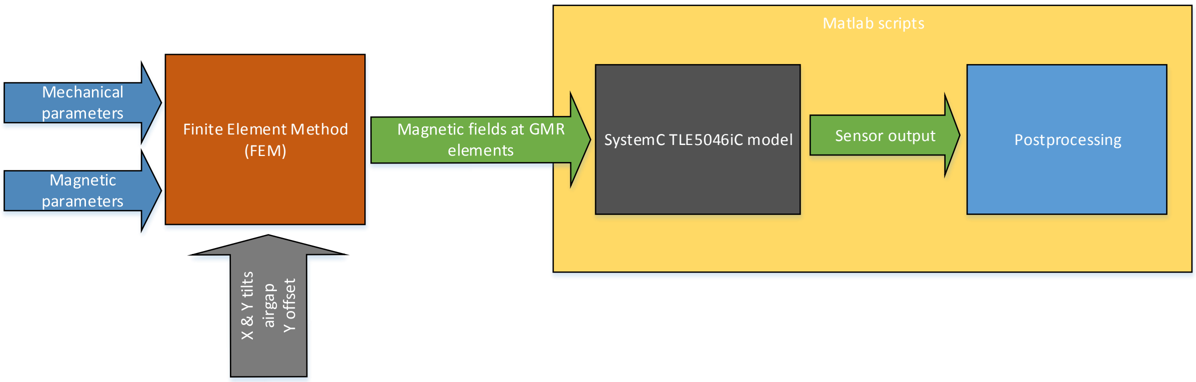

Figure 1. Methodology flow used in this work

In Section II an introduction regarding magnetic speed sensors, product modeling based on SystemC and FEM simulations is provided. Then Section III describes the setup used for the magnetic simulations, the way in which the magnetic simulations are coupled with the sensor model, and how we evaluate the results. Finally, Section IV shows the results and draws the conclusions.

II. BACKGROUND

A. Magnetic speed sensors applications in the automotive industry

Magnetic sensors are widely used in automotive applications. Indeed, they provide a contactless, robust and low-cost solution to sense the position, the rotational speed and the rotational angle of moving parts in wheels, steering system, transmission and engine [2]. Typically, a magnetic encoder is applied to the rotating element and the sensor senses the magnetic field variation generated by the rotation. Alternatively a back bias magnet can be used to generate a constant field that is modulated by the rotation of a steel wheel. To sense the magnetic field different technologies are used. The most common consist in the Hall principle [3] or in the measurement of a magnetic field-dependent resistor such as GMR (Giant Magneto-Resistance) [4], TMR (Tunnel Magneto-Resistance) [5] or AMR (Anisotropic Magneto-Resistance) [6]. Figure 2 shows the most common applications of magnetic sensors in a car.

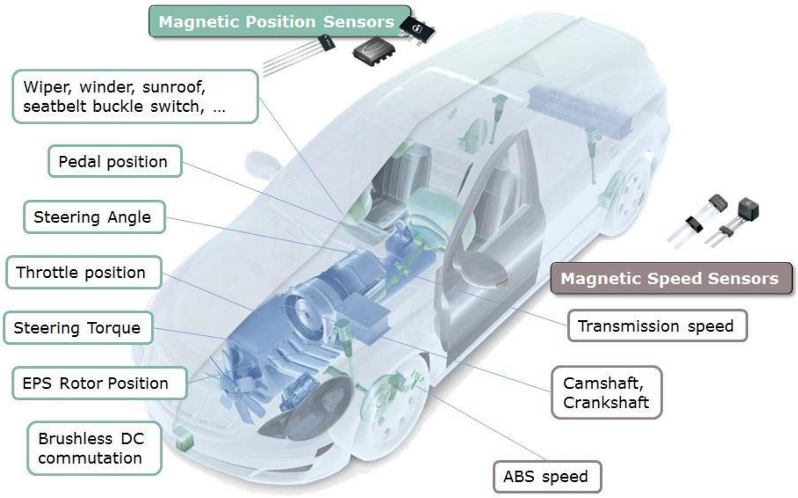

Figure 2. Common automotive applications of magnetic sensors

B. *TLE5046iC: Infineon new generation magnetic speed sensor*

The TLE5046iC is a monolithic integrated wheel speed sensor detecting the rotation of a magnetized encoder using the GMR sensing principle. In particular, three GMR elements are included in the device, to measure the speed and the direction of rotation. The GMRs on the edges (called left and right GMRs) are used to measure the speed, while the one in the center (center GMR) is used to measure the direction. The main features of the TLE5046iC sensors are very low jitter, high sensitivity, immunity against external magnetic disturbances, wide airgap performances and many more. The sensor is connected to an ECU providing information about the wheel speed through a two wire current interface. The sensor is located at the wheels of the vehicle in the wheel mount system. Figure 3 shows the typical usage of the sensor in wheel speed sensing application in the parallel reading configuration. From the picture we can also see some details of the sensor mounting. As explained in Section I, the sensor is normally used in over molded plastic module and connected via cables to the ECU. The sensor located in module is not visible and the module is normally assembled by only one screw and therefore it is very difficult to control exact alignment. Some tilts always could be happened in assembly. Hence, the tilt effects are interesting in wheel speed applications.

Figure 3. Wheel speed sensor position.

C. *SystemC modeling use cases and device model of TLE5046iC*

Product level models based on SystemC are widely used in the semiconductor industry to simulate the behavior of an integrated circuit. A first version of the model can be created very early in the development process, as soon as the product requirements are available. This is useful to reliably assess the clarity and completeness of the requirements definition. Afterward, more details can be implemented into the model to explore different possible architectures and verify the hardware requirements of each block. Finally, the sensor can be simulated in the customers system together with their ECU and actuators.

For TLE5046iC a detailed SystemC model has been developed, to allow fast and accurate simulations. Simulations that in analog and digital circuit simulators would last for hours or days are completed within seconds or minutes, with comparable results (in order to validate the model multiple scenarios have been considered and the output has been compared to the VHDL results). SystemC has been chosen as modeling language because it provides an event-driven simulation interface that enables the designer to simulate concurrent process using C++ language [7]. The COSIDE® environment from COSEDA Technologies GmbH [8] has been used for the development of both the models. In order to develop the model, the device internal block diagram and the product requirements have been used as a reference. To describe the analog modules SystemC-AMS has been used, while for the digital domain the plain SystemC has been chosen. Whenever possible, existing library blocks have been instantiated, but especially for the digital part it was necessary to write specific code to describe the finite state machine behavior. The code has been written in a modular way, to reuse it for similar products in the future.

D. *Finite element analysis use cases and applications*

The finite element method (FEM) is a numerical method for solving complex problems in the areas of electromagnetic potential, heat transfer, fluid flow and structural analysis. These phenomena can be usually described with partial differential equations that often cannot be solved with analytical methods. The finite element method approximates the equations using different types of discretizations and translates the differential equations into a system of algebraic equations [9]. These equations are solved at discrete number of points over the domain, the so called finite elements. Different tools exist to perform FEM simulations. In this work we use ANSYS Maxwell 15.0, an electromagnetic field simulation software for the design and analysis of electric motors, actuators, sensors, transformers and other electromagnetic and electromechanical devices. It provides different kind of solvers, such as Electrostatic, Magnetostatic, Electrical transient, Magnetic transient and many others. For this work the Magnetic Transient with rigid motion solver has been used. We decided to use this tool because both the license and the technical expertise were already available among the authors. In principle, it would be possible to use any other tool supporting FEM magnetic simulations and maybe even SystemC-MDVP (Mutli-Domain Virtual Prototyping). It could be interesting to do that in the future to allow a benchmark comparison in terms of performance and accuracy.

III. METHODOLOGY

A. *Finite element simulation setup*

The setup used in the finite element simulations consists in a magnetic encoder and in a magnetic sensors including three GMRs element mounted parallel to it. This describes well the applications and the only big simplification done is to remove the mechanical piece holding the encoder. Figure 4 shows the whole simulation setup (green axis is X, blue axis is Y, and red axis is Z). Furthermore, the simulated model is simplified by using "Master/Slave boundary" condition thanks to the symmetry of the problem. A detail is shown in Figure 5.

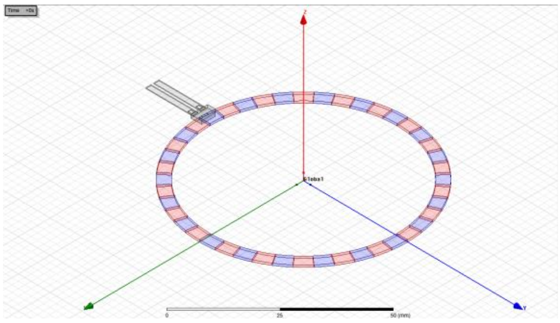

Figure 4. Whole simulation setup.

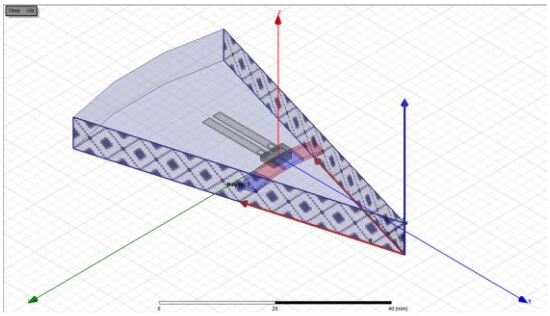

Figure 5. Simplified simulation setup.

The goal of the simulation is to save and observe the magnetic field at the sensing element positions (left, right and center GMRs) when a tilt in the sensor happens around the Y axis (the blue axis in Figure 4). To perform a simulation first of all the objects must be drawn and for doing these the mechanical dimensions are needed. For the magnetic encoder these are:

- 44 pole pairs (44 element with north magnetization, 44 element with south magnetization)
- Inner radius of the magnetic encoder = 29.5 mm
- Outer radius of the magnetic encoder = 32.9 mm
- Height of the magnetic encoder = 0.6 mm
- Magnetization: Axial (Z-axis direction)

Concerning the GMR elements, their geometry has been described according to the TLE5046iC design. The only simplification done here is to assume the height of the GMR negligible. Regarding the magnetic encoder parameter, instead, the data from a real target wheel used in our laboratories has been considered. Once the shapes are defined, the material must be described. The coercivity and remanence values have been chosen to have a good match with the magnetic fields measurement performed in our laboratory (at a certain airgap, without any offset along Y axis).

Finally, the movement should be described. To cover one magnetic period we defined a rotational movement around the z axis with a rotating speed of about 0.4° per second, and we simulated each configuration for 40s (so we have approximately 4° rotation).

The simulation is repeated for the following sweeping parameters for a total of 30 simulations:

- Airgap: 1.1mm, 2.1mm (distance between the magnet and the sensor package)
- Tilt along X axis: 0° (to limit the number of simulations only one value has been given to this parameter)
- Tilt along Y axis: -15°, -7.5°, 0, 7.5°, 15°
- Offset along Y axis: -2mm, 0, 2mm

The boundaries of the sweeping parameters as well as the steps have been defined in order to have enough data to see if there is a trend but limit the simulation overhead in terms of data and time. The X and Y components of magnetic field on the GMR surface are measured for each simulation and the data are saved in tabular and graphical form. The components are defined in the GMR relative reference system (which moves with the sensor when the sensor is tilted). It is important to mention that all the aforementioned mechanical and magnetic values have been defined as parameters, in order to keep the ANSYS model general and suitable for all the speed sensing application in the future.

B. Coupling between finite element results and SystemC simulations

As explained in Section I, the output of the magnetic simulations are used as inputs for the device model based on SystemC. The data from FEM simulations must be pre-processed to be converted into a compatible format. Indeed, the FEM output is a single file containing the results from all the simulations, but for the SystemC simulations different files must be created for each iteration. Moreover, as explained in Section III.A the magnetic simulations have been done with a rotation of only one pole pair (this correspond to only a magnetic period) but to check the behavior of the sensor more magnetic periods are needed. In particular, the model is waiting for the following input files:

- Bx_left, Bx_center, Bx_right
- By_left, By_center, By_right
- Temperature
- Supply voltage

Moreover, the user can set some parameters in a text file. These are:

- R_load: load resistor connecting the sensor to the ECU (in Ohm)
- protocol_name: output protocol to be used
- power_on_time: time in which there is a power-on event, i.e. the supply goes high (in seconds)
- v_supply: amplitude of the supply voltage (in Volt)
- T: ambient temperature (in degree Celsius)
- number_of_periods: number of magnetic field periods
- field_frequency: frequency of magnetic field (in Herz)
- sampling_time: sampling time of the input stimuli (in seconds)

For simplicity the temperature is assumed constant at room temperature of 25°C. The supply voltage instead is a step function from 0 to 15V. Concerning all the other inputs, they are immediately derived from the magnetic simulations. To pre-process the magnetic stimuli, run the simulation and check the functionality, various Matlab scripts have been written to automatize the procedure. The main steps of the software are:

1. The Ansys file containing the magnetic field data of all the simulations is read and the data are saved into the Matlab workspace
2. The parameter file written from the user is read and the data are saved into the Matlab workspace
3. The magnetic field data are sampled again according to the value specified in the *sampling_time* and *field_frequency* parameters

4. The data are repeated for the number of period specified by the user with the *number_of_periods* parameter
5. Pre-processed data are saved in a format that is convenient for the SystemC simulation
6. The SystemC simulation is executed
7. The SystemC output file is post-processed in Matlab
8. A figure is produced and the automatic test described in Section III.C are performed

Steps 3 to 8 are repeated for all the magnetic simulations (30 in our example). It is important to mention that this procedure is device model independent, in the sense that if the model of another speed sensor is used in the future, everything would still work. It would also be easy to adapt the procedure for angle or position sensors, but in that case a new magneto-mechanical model should first be designed in the ANSYS environment.

C. Results evaluation

As explained in Section I, the goal of this work is to see the effect of tilting on the magnetic field and on the sensor output. For the first task it is enough to analyze the output of the magnetic simulations. For the second, the information coming from the SystemC simulations must be post-processed and evaluated. In particular, we check the following:

- If the sensor goes into the calibrated mode of operation, i.e. the sensor generates a new protocol when the magnetic field crosses the zero threshold
- If in calibrated mode the duty cycle of the output protocol is within the requirements (40% - 60%)

Both the checks are performed automatically in Matlab processing the internal calibration signal and the output current signals. The Matlab script at the end returns if all the tests have been passed and if not specifies the name of the tests that failed. Moreover, a bar chart is produced showing the average duty cycle error for each simulation, in order to try to find a trend in the results.

IV. RESULTS AND CONCLUSIONS

A. Effects of the tilts and Y offset on the magnetic field

The following trends can be found in the amplitude of magnetic field (X and Y components):

- Positive tilt around Y axis: the magnetic field measured from the right GMR is bigger than the magnetic field measured from the left GMR.
- Negative tilt around Y axis: the magnetic field measured from the left GMR is bigger than the magnetic field measured from the right GMR.

Moreover the following happens

- Positive offset along Y axis: X component of magnetic becomes weaker, while the Y component of the magnetic field becomes stronger. Moreover the wheel pitch seen by the sensor increases because the sensor moves to the outside of the wheel.
- Negative offset along Y axis: X component of magnetic becomes weaker, while the Y component of the magnetic field becomes stronger. Moreover the wheel pitch seen by the sensor decreases because the sensor moves to the inside of the wheel.
- Increase the airgap: the amplitude of the magnetic field at all the three GMR elements decreases.
- Decrease the airgap: the amplitude of the magnetic field at all the three GMR elements increases.

As an example, Figures 6 and 7 show the results for 1.1mm airgap and two different Y offsets (0 and 2mm). The following legend has been used: blue for the magnetic field at the left GMR, green for the magnetic field at the center GMR, yellow for the magnetic field at the right GMR.

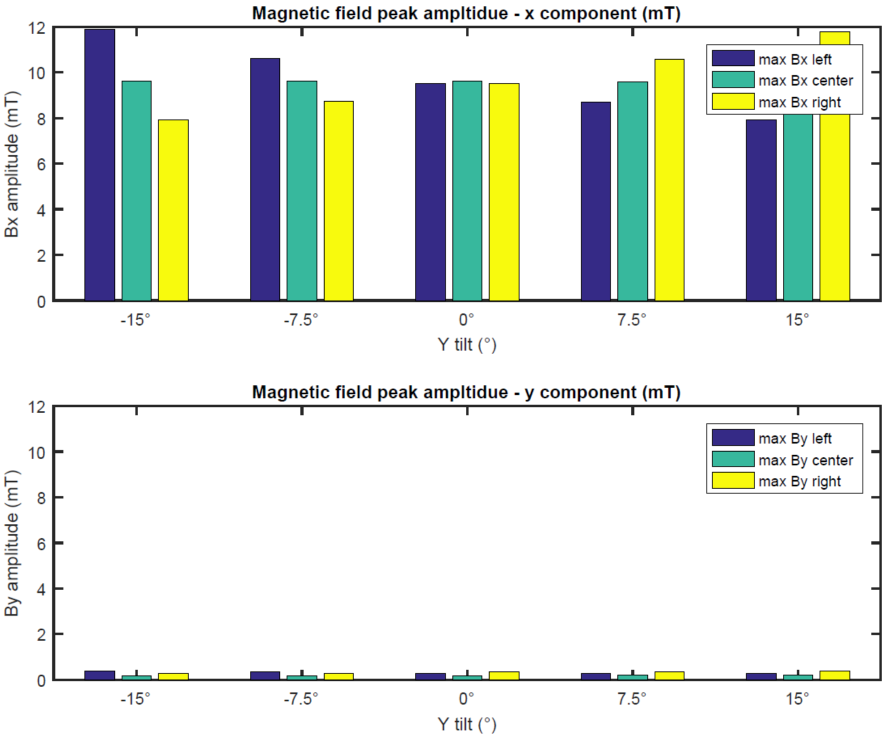

Figure 6. Effects of tilt around Y axis on the magnetic field amplitude (airgap = 1.1mm, Y offset = 0)

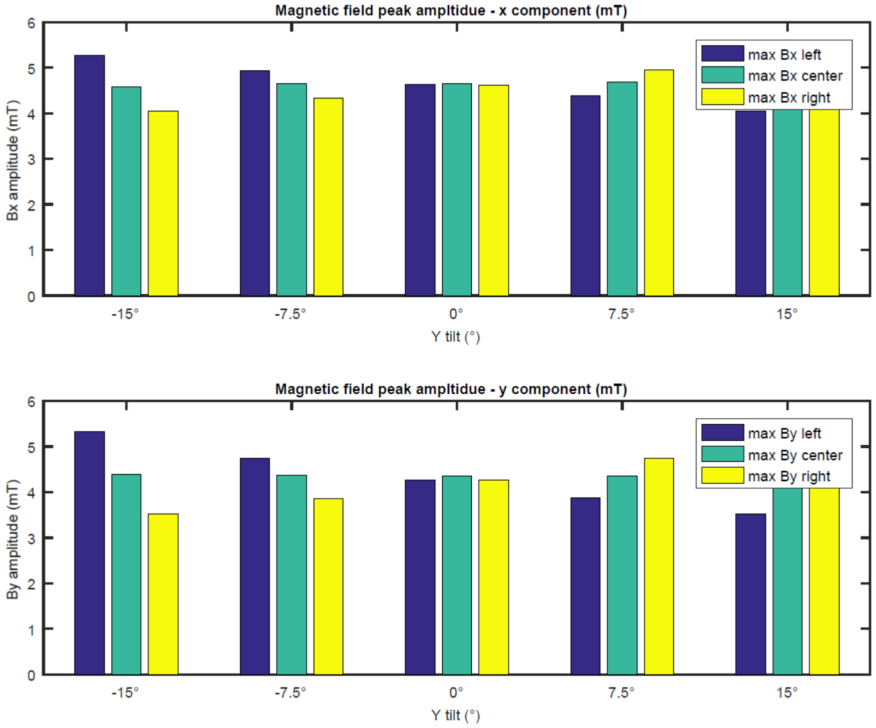

Figure 7. Effects of tilt around Y axis on the magnetic field amplitude (airgap = 1.1mm, Y offset = 2mm)

B. *Effects of the tilts and Y offset on the sensor performances*

Beside the results shown in Section IV.A, in this work we tried to evaluate also the effects of different Y offset and Y tilts on the duty cycle of the output signal of the TLE5046iC. Our simulations shows that in all the evaluated scenarios the sensor manages to go into calibrated mode and that the duty cycle is always within the limits specified in the requirements. This helped us to proof again the reliability and robustness of the sensors, which is able to work also with mechanical assembly deviation, as already shown previously from our measurements done on the real hardware. In addition, a second goal was to try to find a correlation between the simulation results and the data from the laboratory measurements. The initial results are promising, though additional work is necessary to achieve the desired accuracy. On this regard, we need to consider the following:

- By field effects on the GMR model are very complicated to describe accurately. In our SystemC model the Stoner Wohlfarth [10] model was used, which provides a good description of the device physics and includes the By effects. The model is configurable via many parameters and this means that it could be tuned to get a behavior which is even closer to the real technology.
- The FEM simulated model was developed using raw magnet material properties. However, in the materials used in a real magnetic encoder there are different magnetic properties due to specific magnetic design and magnetized condition. Moreover, the simulation is not considering minor components such as magnet holder and fixed jigs. Therefore, the Bx and By configuration obtained from our FEM simulations are also not exactly matching with the real magnetic field.

For these reasons, we decided not to show the trend found in the results in this work, in order to not confuse the reader with information that may be erroneous.

C. Conclusions and future work

In this work we proved a complete simulation flow, from the mechanical and magnetic definition of the scenario used in a wheel speed sensing application, to the analysis of the output protocol of the sensor. The data from FEM simulations have been used as input to a sensor model based on SystemC. The data have been then analyzed and post processed in Matlab in a fully automatic way. This methodology is useful in the automotive industry to design, test and explore different application scenarios and new integrated circuits and is often used in Infineon and from our customers. The results obtained are already interesting and can help the reader to understand better what happens in case of mechanical tilts and misplacements during the mounting of the sensor. However, various improvements could be done in the future work on this topic, such as:

1. Be more confident about the Bx and By configuration obtained from the FEM simulations, maybe using some correction factors to have a better matching between the measured and the simulated magnetic fields.
2. Refine the GMR model to describe more accurately the second order effects due to By field component.
3. Find a more accurate matching between the trend shown in the simulations and the measurements.

Moreover, more scenarios could be considered, as for example combining the X and Y tilts at the same time, or simulating also for smaller and bigger airgaps.

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