GOUDSMIT
MAGNETICS

Robust Design of Magnet-Hall Sensor Combinations

September 2022

Introduction

In this white paper we discuss how Goudsmit uses finite-element-method (FEM) computations in the design of magnet-Hall sensor systems.
In particular we look at how manufacturing imperfections may affect the design of a magnet-Hall sensor system and how we at Goudsmit exploit known manufacturing tolerances to provide a *robust* design of these systems, with minimum failure rate for these systems while in actual operation.

FEM computations to benefit the design of magnet-Hall sensor systems

Hall sensors are electric devices that are sensitive to magnetic fields and transform the sensed magnetic field in a proportional voltage output signal. As a consequence, exploiting this sensitivity, this type of sensor has found widespread use in industry in combination with a magnet for contactless proximity sensing, position and speed detection, for example in automotive systems and consumer electronics. The magnet is then typically contained in the moving part while the sensor is contained in the stationary part, or vice versa, and the output electric signal of the Hall sensor changes as a function of the distance of the magnet to this element.

Such magnet-Hall sensor combinations allow not only for measurement of magnetic field strengths but also for applications as, for example, sensing whether a door is open or closed, for sensing whether the seat belt in a car is locked, for measuring the distance towards a surface in magnetic levitation applications or for measuring the rotational speed of a wheel. These – typically hidden - detection systems can be found in many products and industrial manufacturing systems.

A single magnet-Hall sensor system is relatively in-expensive. They are often used in mass produced products or systems. For these large volume applications it pays off to perform dedicated research for the cheapest solution that still meets performance requirements. An important and costly component is the magnet. Especially in the last years while prices of magnets are steadily increasing due to geo-political factors concerning its rare earth elements.

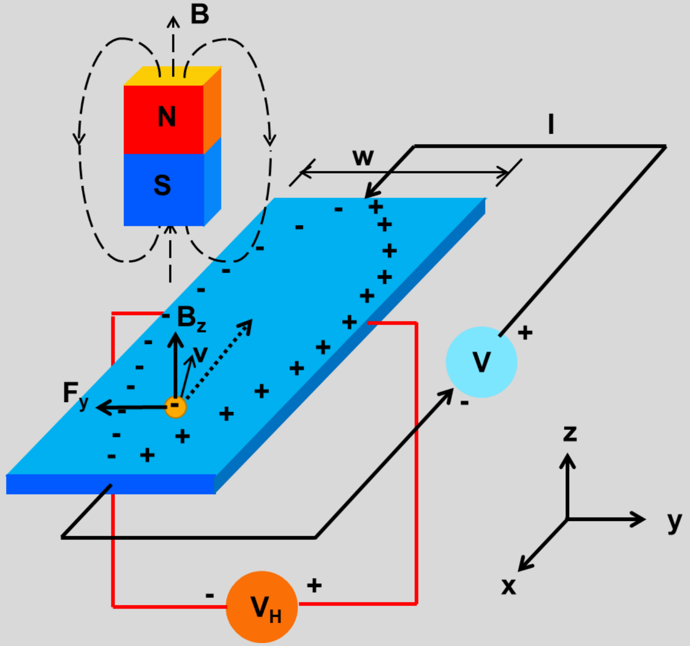
Simultaneously, like any manufactured system, the elements of a magnet-Hall sensor system are subject to manufacturing imperfections, as specified in terms of tolerances with respect to the dimensions and magnetic characteristics of the magnet and the dimensions and sensing characteristics of the Hall sensor. When not considered in the design, the manufacturing imperfections may lead to a relatively large failure rate and, thereby, large costs. To reduce these costs to a minimum, Goudsmit has developed a robust design method, at the heart of which lies the usage of FEM computations.

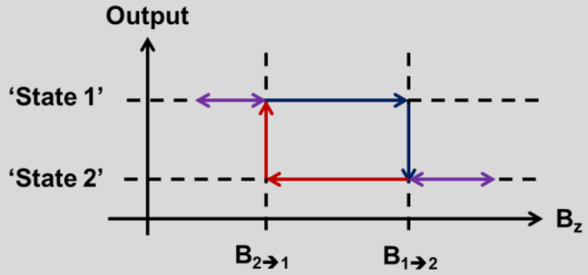
The Hall Sensor

The Hall sensor makes use of the *Hall effect.* This effect, which was discovered in 1879 by the American physicist Edwin Herbert Hall, is schematically depicted in the figure on the right. It is the phenomenon that, when a magnetic field (B) is applied perpendicular to a (flat) conductor with a certain width (w) through which an electric current (I) flows, a voltage difference – the so called Hall voltage (V_H) - is obtained along this width transverse to this current. It is a consequence of the fact that the magnetic field, more specific its component perpendicular to the conductor surface (B_z), exerts a force on the electrons flowing through the conductor, which is called the Lorentz force. This force (F_y) is directed transverse to the direction of the current I (in the y-direction in the figure) and causes the electrons to move more along one side of the conductor. The resulting difference in electron and charge density over the conductor width creates the Hall voltage. The amplitude and sign of this voltage depend on the amplitude and direction of the applied magnetic field, and hence on the strength, proximity and orientation of the applied magnet.

Hall sensors can be made into millimeter-sized devices and sensitive to relatively small magnetic flux densities in the order of 1 to 100 mT. As a consequence, these can be combined with relatively small magnets to provide small and easy to hide contactless proximity, position and speeds sensing systems. Being contactless, these systems are less prone to wear and, hence, are showing less mechanical failures.

The most common types of Hall sensor are of the linear (analogue) type or of the (digital) switch type. A linear type of Hall sensor provides an output voltage signal proportional to the sensed magnetic flux density (with range limitations determined by saturation effects). With a common switch type of Hall sensor, the sensed signal is compared to a pre-set (threshold) value and when it exceeds this value the Hall sensor output signal switches from one constant level to another constant level. When, subsequently, the sensed signal becomes smaller and passes another pre-set value, the Hall sensor output signal switches back to the original constant level. The two pre-set values are separated by a (hysteresis) value to avoid any undesired oscillations in the sensor output signal. .





Schematic view of the operation of a common switch type of Hall sensor. When the sensed magnetic flux density B_z increases (purple-blue line) and exceeds the value $B_{1\to2}$, the Hall sensor output signal switches from state 1, which corresponds to a constant high output level and represents e.g. an 'ON' ('OFF') situation, to state 2, which corresponds to a constant low output level and represents e.g. an 'OFF' ('ON') situation. When B_z subsequently decreases in value (purple-red line) and passes the $B_{2\to1}$ threshold value it switches back to state 1 .

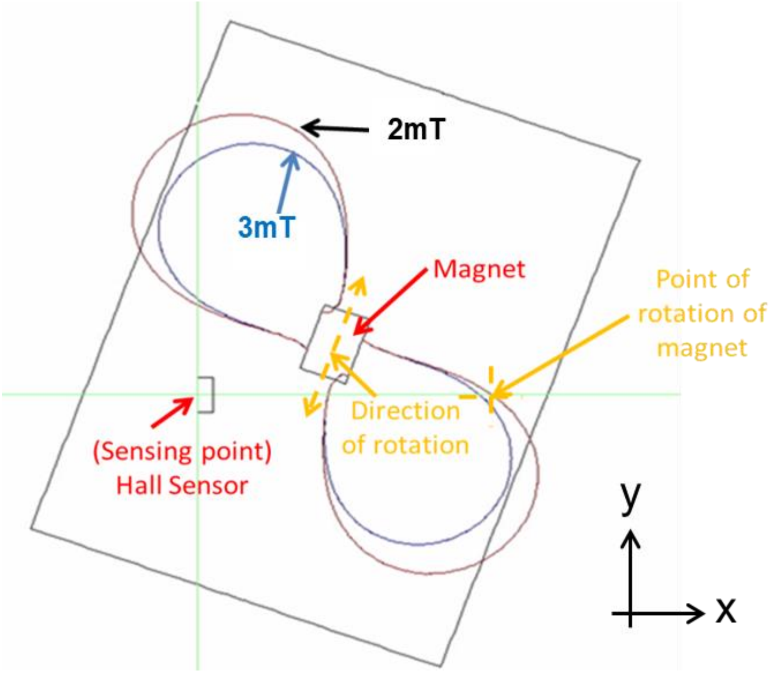
Design of Hall sensor combinations

The design of magnet-Hall sensor systems involves magnet and sensor selection and determination of the relative location or movement of the magnet with respect to the sensor, such that obtained sensing is according to the requirements.

Goudsmit employs finite-element-modelling (FEM) computations for the design of magnet-Hall sensor combinations (and other systems). In particular, we use FEM to compute the magnetic flux density sensed by the sensor as a function of the location/movement of the magnet relative to the sensor.

With the FEM method, a mathematical model of the system is built by drawing an approximation of its geometry and dividing this geometry into many small elements c.q. volumes. For each of the volumes, a set of equations is then formulated that is an approximation of the elementary physics equations valid at this volume (these equations are actually valid at a point rather than over a volume). The equations for all elements are then combined and simultaneously solved to provide the system performance parameter values of interest. FEM is a well-established means of modelling and analyzing physical systems in the industry. While computationally relatively expensive, it is also relative accurate. Goudsmit makes use of the software package Comsol for its FEM modelling projects [1, 2].

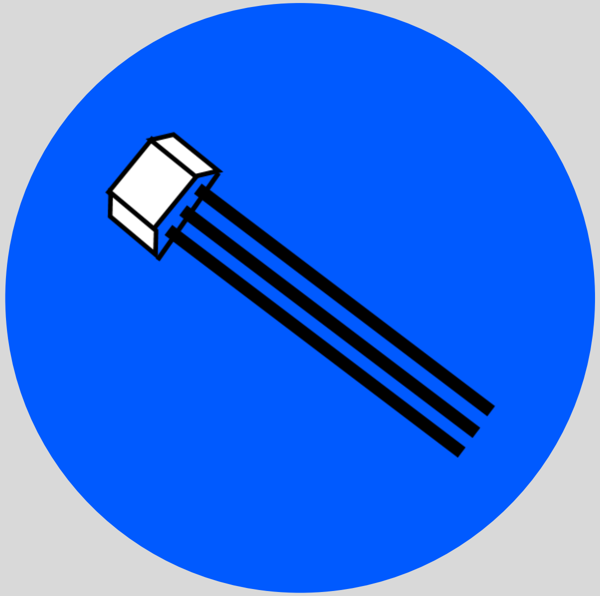
An outcome of a FEM based design of a magnet-Hall sensor combination is depicted in the figure on the right, demonstrating the usage of a switch type of Hall sensor. It shows a magnet with contours around this magnet of equal magnitude of the magnetic flux density in the x-direction. The magnet rotates and when the 3mT contour passes the Hall element in the sensor, which may be modelled as a point due to its relatively small size, the sensor switches from state 1 (e.g. an ‘ON’ state) to state 2 (an ‘OFF’ state). When the magnet rotates back, the sensor switches back from 2 to 1 (from ‘OFF’ to ‘ON’) when the 2mT contour passes this sensing point. The aim of the computation here was to find the angles at which the switchings take place, to determine whether these fullfill the corresponding specifications.



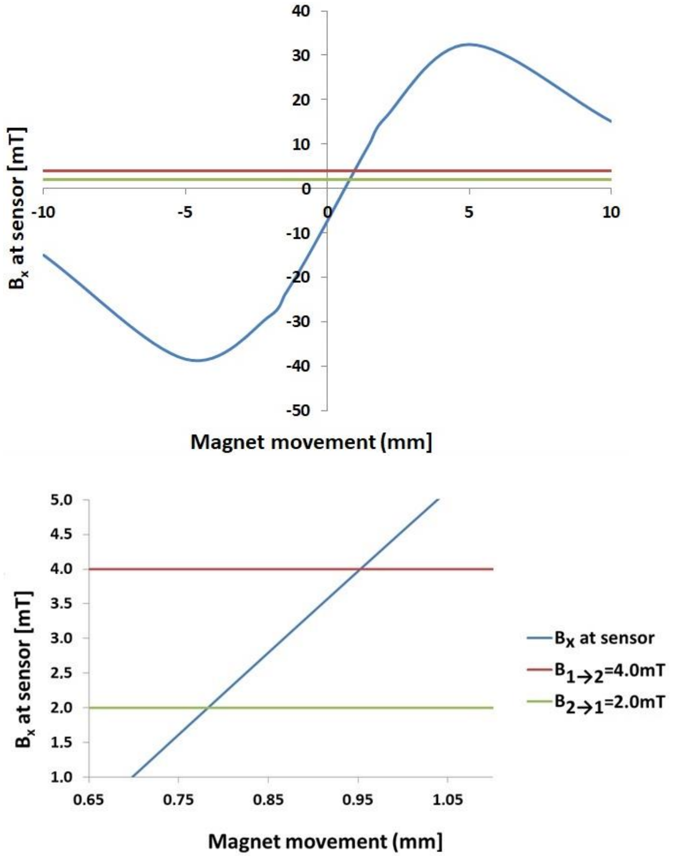
2D results from a 3D FEM computation for a rotating magnet-Hall sensor application. The sensor is of the switch type with $B_{2\rightarrow 1}$=2mT and $B_{1\rightarrow 2}$=3mT.

Design of Hall sensor combinations

A FEM computation result from another magnet-Hall sensor design exercise is depicted here on the right. Here, the relevant magnetic flux density component (x) at the sensitive point of the sensor, as computed by FEM, is shown as a function of the movement of the magnet. By showing the nominal threshold switching values $B_{1\rightarrow2}$ and $B_{2\rightarrow1}$ as well, the magnet locations where the switchings take place can readily be obtained from the figure.

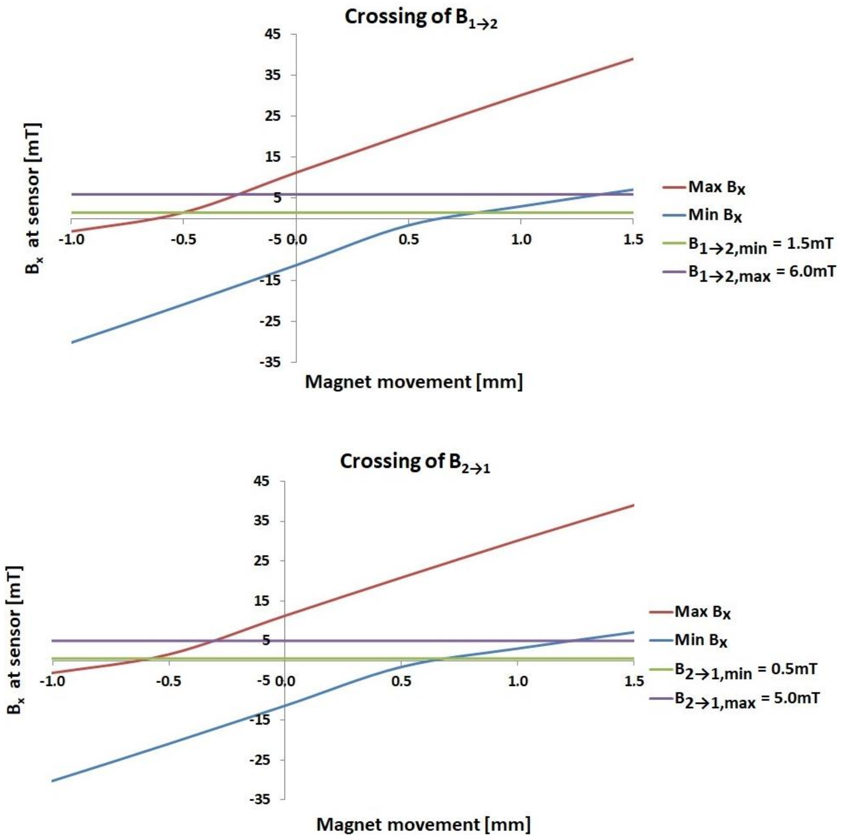


A typical layout for a Hall sensor



FEM computation results for a magnet-Hall sensor application where the magnet moves along a straight line, passing a nearby Hall sensor. The sensor is of the switch type with $B_{2\rightarrow1}$=2mT and $B_{1\rightarrow2}$=4mT. According to these results, the switch from state 1 to 2 takes place at a magnet location of (approx.) 0.95 mm and the switch from state 2 to 1 takes place at a location of (approx.) 0.78mm.

Robust design of Magnet-Hall sensor combinations



Goudsmit FEM computation results for robust design of a magnet-Hall sensor system where the magnet moves along a straight line, passing a nearby Hall sensor. The sensor is of the switch type.

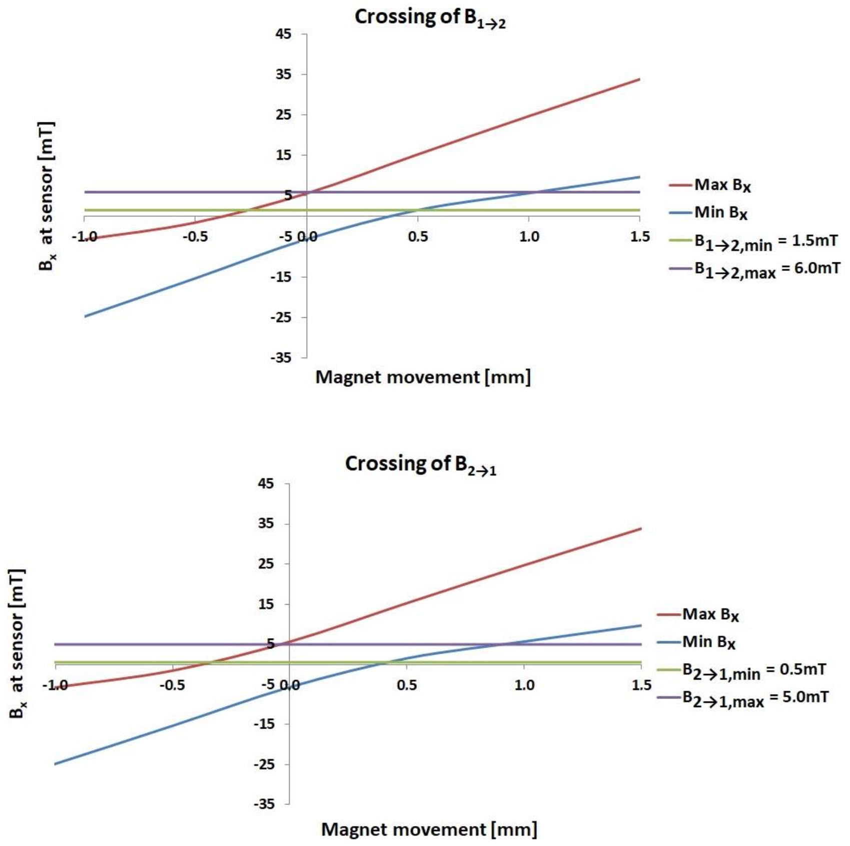
The design examples discussed at the previous pages do not take into account uncertainties in the design such as those present in (i) the magnetic properties and dimensions of the magnet, (ii) the sensing characteristics and dimensions of the Hall sensor and (iii) the distance between the magnet and the sensor, which all are typically expressed via manufacturing tolerances in terms of a minimum and maximum value. When not taking these uncertainties into account in the design, the actually manufactured magnet-Hall sensor combination may be quite different in dimensions and performance compared to the assumptions and predictions made in the design phase. In the presence of many and/or relatively large tolerance limits this performance may even become non-acceptable, even though the design exhibited an acceptable performance. This can be dealt with by taking a so called *robust* design approach, where these uncertainties *are* taken into account..

A system parameter that is uncertain and defined in terms of tolerances, with a range with an upper and lower bound, can take on many values within this range. For each of these values the magnetic flux density sensed by the Hall sensor will be somewhat different. As a consequence, considering all possible values of the uncertain system parameter within its tolerance limits, the sensed magnetic flux density will also be lying within a range with upper and lower limit. At the core of the Goudsmit FEM approach to robust design of magnet-Hall sensor systems lies the ability to efficiently compute this range. In case of switch type of Hall sensor applications, this is then exploited to determine the magnet movement *ranges* where the threshold values are crossed. The robust design approach then focuses on reducing or moving these ranges until the threshold crossing magnet location requirements are met. For instance by choosing higher quality products with tighter tolerances.

A result of this Goudsmit range computation approach, which follows up on the example considered at the previous page, is given here on the left. Note that now both the crossing of the $B_{1\rightarrow 2}$ and $B_{2\rightarrow 1}$ threshold values are not specified anymore in terms of a specific magnet movement (*point*) value, as on the previous page, but, indeed, in terms of a range. For example, if the $B_{1\rightarrow 2}$ threshold value would be 1.5mT (purple line) the crossing would be for a magnet movement value somewhere between approximately -0.25mm (crossing with the red line) and 1.4mm (crossing with the blue line). Given the uncertainties defined by the tolerances it could be *anywhere* within this range. Note that this may be a much too wide range for the considered application, requiring then an adaptation to the design.

As can be seen from the figure on the left, the Goudsmit approach also explicitly takes tolerances on the threshold values into account, with the maximum and minimum values obtained from the sensor specifications and shown here as purple and green lines. The crossing ranges actually are now between the first crossing of the minimum threshold value (crossing red with green line) and the last crossing of the maximum threshold value (crossing blue with purple line).

Robust design of Magnet-Hall sensor combinations



Goudsmit FEM computation results for robust design of a magnet-Hall sensor system where the magnet moves along a straight line, passing a nearby Hall sensor. The sensor is of the switch type. The results are obtained with the same system as on the previous page but with a magnet with maximum magnetization direction deviation of 3º instead of 6º.

The Goudsmit FEM approach to robust design of magnet-Hall sensor systems delivers two crossing ranges. One for the $B_{1\rightarrow2}$ threshold value, and one for the $B_{2\rightarrow1}$ threshold value. The computation of these ranges, while providing a qualitative description of the effect of system uncertainties on its performance, may take long and require much memory storage capacity. A key characteristic of the Goudsmit approach is that required time and storage capacity is reduced by making clever choices with respect to the FEM computations. In making these choices, knowledge of the characteristics of the magnet and its radiated magnetic flied are, amongst others, exploited.

Computation of magnet movement ranges can help in robustifying the design by adapting it such that these ranges shrink in size and/or are shifted to another movement range. Thus ensuring a better or completely guaranteed fulfillment of the specifications on the state change locations or ranges. It can also reduce the failure rate and associated costs. The shrink in size and shift in location of the threshold passing ranges can be established by changing the sensor characteristics and/or magnet characteristics and/or their relative position.

To provide an idea of this shrink in range size, consider again the example application of the previous page. The results there were obtained by using a magnet with a maximum deviation on the magnetization direction of 6 degrees. Such deviations from the straight north-south direction of the magnetization arise from manufacturing inaccuracies. Several magnet qualities can be purchased, each having a different maximum deviation in magnetization direction and cost. The smaller this maximum deviation the higher the cost of the magnet.

In this example computation results are depicted for the same system as discussed on the previous page, but now with a higher magnet quality. This time with a maximum magnetization direction angle deviation of 3 degrees instead of 6 degrees. As can be observed, the threshold crossing ranges are now significantly reduced in size. More specific, the crossing range for the $B_{1\rightarrow2}$ threshold value has been reduced from approximately 2.0mm (-0.6mm ➔ 1.4mm) for a magnet with maximum magnetization direction deviation of 6º to approximately 1.3mm (-0.3mm ➔ 1.0mm) for a magnet with maximum magnetization direction deviation of 3º. Likewise, the crossing range for the $B_{2\rightarrow1}$ threshold value has been reduced from approximately 1.9mm (-0.6mm ➔ 1.3mm) for a magnet with maximum magnetization direction deviation of 6º to approximately 1.2mm (-0.3mm ➔ 0.9mm) for a magnet with maximum magnetization direction deviation of 3º.

Conclusions

Magnet-Hall sensor combinations are found in many industrial systems for contactless proximity sensing, position and speed detection. Goudsmit can support the design of these systems by means of a finite-element modelling (FEM) based approach. With this approach the system can be tested and optimized in a simulation environment early in the design phase. This helps to significantly reduce development costs by avoiding numerous tests with real-life magnets.

The Goudsmit FEM approach to magnet-Hall sensor system design has been outlined in this white paper and examples on switch type of Hall sensors have been used to illustrate its characteristics. Recently, Goudsmit has extended this approach to also take system parameter uncertainties into account, as quantified by tolerances on magnet characteristics, sensor characteristics and relative distance between magnet and sensor. This approach can be used to obtain a more robust design, leading to a stricter fulfillment of system specifications and lower failure rates. Key characteristic of this robust design approach is that by exploiting Goudsmits knowledge of magnets, clever choices can be made with respect to the simulations. Thereby, the overall simulation time, and with it, product development time is reduced significantly.

References

[1] Leskens, M. & C. van de Paal (2019.
Optimization of Magnetic Systems through Finite Element Modelling.
15th XMR Symposium on Magnetoresistive Sensors & Magnetic
Systems, 19-20th March 2019 – Wetzlar, Germany .

[2] COMSOL Multiphysics® Modeling Software: https://www.COMSOL.com.

Youtube

FEM calculations for magnetic filters (steel):
https://youtu.be/97RcfKic3y8

FEM calculations for magnetic filters (stainless steel particles) :
https://youtu.be/OOaClbPLxCs

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More information about FEM calculations at Goudsmit?

https://www.goudsmitmagnets.com/solutions/service/calculation-and-simulation.html

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