GOUDSMIT MAGNETICS

Optimisation of Magnetic Systems through Finite-Element Modelling

Presented at the 15th XMR Symposium on Magnetoresistive Sensors & Magnetic Systems, 19-20th March 2019 – Wetzlar, Germany

Abstract

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Finite-element modelling (FEM) is a well-established means for system analysis and optimisation that can substantially reduce product development time and costs. With this modelling tool the domain of interest is split up in small elements over each of which the fundamental physics equations are solved. For a company involved in magnetics such as Goudsmit Magnetic Systems it is an important tool because of the ability of relatively accurately predicting the performance of its electro-magnetic systems. In this paper the FEM method, as currently applied at Goudsmit, is outlined in more detail and a variety of applications of this method are discussed, as encountered at Goudsmit. This serves to provide an idea of both how FEM can be used for the analysis and optimisation of magnetic systems and of the diversity of industrial applications where magnetics is involved. For some applications it is not sufficient to only model the electro-magnetic phenomena but other physical phenomena as well, in particular the product flow in case of separation applications.

Introduction

Current premises of Goudsmit Magnetics in Waalre – the Netherlands

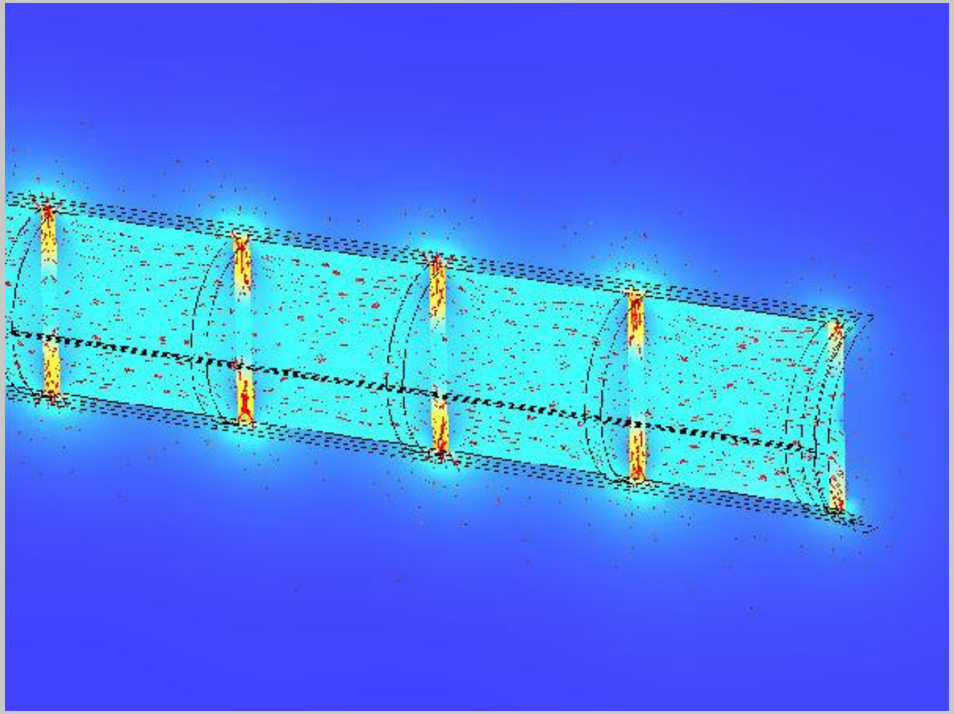
Finite-element modelling (FEM) is a well-established means for modelling and analysing physical systems such as encountered in the high-tech manufacturing, aerospace and (petro-) chemical industry. A main driver for its usage is the reduction of time and costs spent on prototype design and testing. It is used to model for example electro-magnetic and fluid and heat flow phenomena, and to perform mechanical type strength calculations. With FEM, elementary physics equations in the form of partial differential or integral equations are solved over (many) small elements into which the system of interest is divided. While typically computationally more expensive than other approaches, it may also lead to more accurate answers.

Founded in 1959, Goudsmit Magnetics is a company of about 140 employees with headquarters in Waalre, the Netherlands. It produces (electro-)magnetic systems for the food, automotive and recycling industry. Goudsmit has been using FEM for many years for analysing and optimising its systems. Main reason for that is, apart from reduction in prototype development and testing costs, the relatively accurate performance predictions that can be made with this tool. It has become an important means for product development and, as such, plays an increasingly important role in staying ahead of competition.

For a few years Goudsmit's used the FEM package COMSOL [Co18], largely because of its ability to combine different physical domains. In particular, this ability allows for an extended evaluation of electro-magnetic systems in the sense of evaluating the effect of non-magnetic phenomena on the overall performance of the magnetic systems as well, such as heat production in coil related applications and the effect of flow characteristics on the efficiency of magnetic separation systems.

One of the aims of this paper is to present the state-of-the-art on how FEM is applied in a company specialised in electro-magnetics such as Goudsmit. Another aim is to provide an idea of the variety of electro-magnetic applications that is handled by such a company. These aims are fulfilled by, first of all, providing a brief introduction into FEM for magnetic system applications and, subsequently, by discussing a number of FEM applications encountered in daily practice. These applications represent both internal product development and optimisation projects, system evaluations and optimisation for external customers.

Contents



FEM for magnetic system applications

The contents of this paper is as follows:

Finite-element modeling for magnetic applications

- What is FEM?
- An introduction into FEM for magnetic system applications
- Outline of a specific – but generic – FEM approach as applied at Goudsmit

FEM applications at Goudsmit

- Overview of various FEM applications encountered in daily Goudsmit practice
- More detailed discussion of how FEM is used to model and optimise magnetic separation systems
- Recycling systems
- Magnetic handling devices
- Magnet-Hall sensor combinations

Conclusions

Finite-element modelling for magnetic applications

What is FEM?

Physical systems are typically described by partial differential equations or integral equations. Rather than analytically solving these equations, which is difficult or infeasible for most practical problems, FEM (also referred to as finite-element analysis or FEA) solves these equations numerically and approximatively. This is done by dividing the domain of interest into small elements, setting up a relatively simple set of equations for each element and collect these in a larger set of algebraic equations that models the full system. This set of equations is then solved numerically by minimising some error function. The computed solution approaches the true – analytical - solution as the elements are chosen smaller.

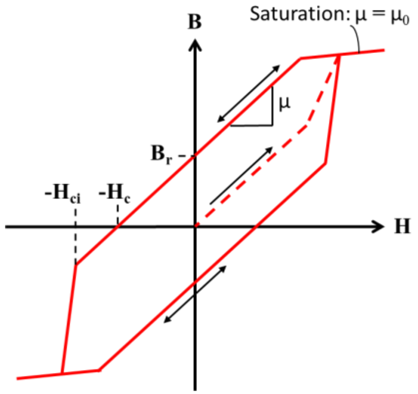
Generic setup of the FEM approach

The generic setup of the FEM approach may be formulated as follows:

- Modelling of relevant geometry
- Allocation of relevant materials and material properties to the geometry elements
- Choice of relevant physics
- Division of the geometry in small elements, i.e. volumes, over which the physics is to be solved. This is also referred to as 'meshing'
- Choice of numerical solver and solver settings
- Numerical solution of the resulting model
- Post-processing of the computed results

This approach is typically an iterative approach, i.e. the steps of these approach are not executed one-way-through only but may require adaptation and re-execution of earlier steps.
The geometry may be built from scratch by the modeller but may also be inserted as a CAD-file, e.g. when provided by a customer. Non-relevant parts of system to be modelled should be excluded as much as possible from the geometry to, particularly, avoid too long computation times. Geometries may be 2D or 3D. Modelling in 2D will lead to lower computation times but also lower accuracy.

For magnetic applications, it is of particular importance to include the relevant magnetic material properties like e.g. the relative magnetic permeability and remanent flux density of the material or the full **B**-**H** curve of the material. COMSOL or other material libraries may be exploited here, or other sources like books (e.g. [Sv04]) or websites. It is noted that the linearity of the implemented **B**-**H** curve can significantly affect the convergence rate of the resulting numerical FEM problem.



B: magnetic flux density (Tesla (T))
H: magnetic field strength / intensity (Ampére/meter (A/m))
μ : magnetic permeability (Henry/meter (H/m))
B_r: remanent magnetic flux density / remanence (T)
H_c: coercivity / coersive force (A/m)
H_{ci}: intrinsic coercivity / intrinsic coersive force (A/m)
μ_0 : magnetic permeability of vacuum = $4\pi\cdot10^{-7}$ (H/m)

Schematic view of a permanent (hard) magnetic material **B**–**H** ('hysteresis') curve & some common nomenclature. For soft magnetic materials the area between the lines is much smaller or even zero.

The physics behind (electro-)magnetic applications are contained in Maxwell's equations, which – in differential form – are stated as (see e.g. [Kr91])

(Gauss's law:)	$\nabla \cdot \mathbf{E} = \rho/\varepsilon_0$	(1)
(Gauss's law for magnetism:)	$\nabla \cdot \mathbf{B} = 0$	(2)
(Maxwell-Faraday equation:)	$\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$	(3)
(Ampère's circuital law:)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \partial\mathbf{E}/\partial t$	(4)

Finite-element modelling for magnetic applications continued

Of the computed quantities, the values for the magnetic flux density **B** (SI unit Tesla (T) but often expressed in Gauss (G) with 1T=10000G) are often of most interest for practical applications, together with the values computed for some force or torque as derived from these quantities. It is noted that the magnetic circuit modelling approach uses a subset of Maxwell's equations in simplified form.

Not all of Maxwell's equations may be needed for an application. For instance, for pure permanent magnet applications the electrics part of these equations part is not relevant and may be discarded, which can lead to a considerable reduction in computation time. Inherent to Maxwell's equations are well-known physical phenomena as that (i) an electric current in a wire (straight or coil) causes a magnetic field around this wire and (ii) a time-varying magnetic field in a conductor causes electric currents in this conductor (eddy-currents).

The finer the mesh used for dividing the geometry in small elements, the more accurate the solution, but also the longer it takes to numerically solve the model. In practice, meshing is typically about finding a good compromise between accuracy and solution time, which sometimes can even be in the order of days or weeks. Other aspects of meshing include the choice of element type/shape (often tetrahedral in 3D problems).

A numerically solver aims for minimising some error function. Although often standard numerical solver settings may suffice for the problem at hand, i.e. will lead to convergence of this error function to a value sufficiently close to zero, sometimes one may need to adapt these settings or use another solver.
Post-processing of the resulting quantities is used to visualise the computed values and translate these into data into which the customer is actually interested, in the form of pictures, tables or movies.

As mentioned in the introductory part of this paper, a main driver for Goudsmit to use the FEM package COMSOL is that it allows for combining different types of physics. For example, it allows for combining electro-magnetic computations with flow computations. This is relevant for magnetic separation applications where flow properties such as velocity and viscosity can have a large impact on the separation efficiency. Solving for flow is typically done through numerically solving microscopic conservation equations (mass, momentum, …)), assuming the fluid to be a continuum. The branch of science studying this subject is called Computational Fluid Dynamics (CFD). Of fundamental importance for CFD is the solution to the momentum balance known as the Navier-Stokes equation. It is outside the scope of this paper to discuss all aspects of CFD.
Likewise, it is outside the scope here to discuss all aspects of FEM, which are considerably more than outlined here.

FEM applications at Goudsmit

Overview
Being a company, the majority of FEM applications encountered at Goudsmit naturally reflect the commercial applications it is involved in. These applications are related to current or future product analyses and improvements for both (external) customers and internal departments. Sometimes, FEM material is also used for sales purposes or manufacturing analysis and optimisation.

The FEM applications also reflect the markets Goudsmit is involved in. The main markets for Goudsmit include:

Metal separation, where metal is seen as an undesired component that needs to be separated from the main product flow, e.g. for reasons of health, safety and/or environment. An important market here is the food industry.

Metal & waste recycling, where the metals to be separated are seen as valuable, i.e. as having a commercial value. Not only ferrous - magnetic or magnetisable - objects may be separated here but also non-ferrous conductive objects (e.g. made of aluminium or copper). The separation is then not based on magnetic attraction but rather on repulsive forces created by eddy-currents introduced through a time-varying magnetic field.

Magnetic handling, where magnets are used to pick up and move, or to fixate (ferro-)metallic objects, e.g. as part of a robotic arm. These applications are typically found in the manufacturing industry (metal, automotive, robot), for example for automation purposes.

Demagnetisation, where coils and time-varying currents are used to demagnetise material to a sufficiently low level (typically in the order of 1 – 10 Gauss). Undesired magnetism present in objects such as e.g. pipelines may hinder welding.

Automotive and consumer electronics. Although typically not directly visible to the eye, cars and consumer electronics contain a significant amount of (electro-)magnet systems. A well known example is the electromotor. Perhaps less well known is that many automotive and consumer-electronics devices contain magnets in combination with a Hall sensor for position detection or (de-)activation of system parts.

Modelling and optimisation of magnetic separation systems

A magnetic filter

Magnetic separation systems are used to filter out undesired metallic particles from gaseous, liquid, solid (powder) or multi-phase (e.g. gas-powder) mixtures type product flows, as for example found in the food industry.

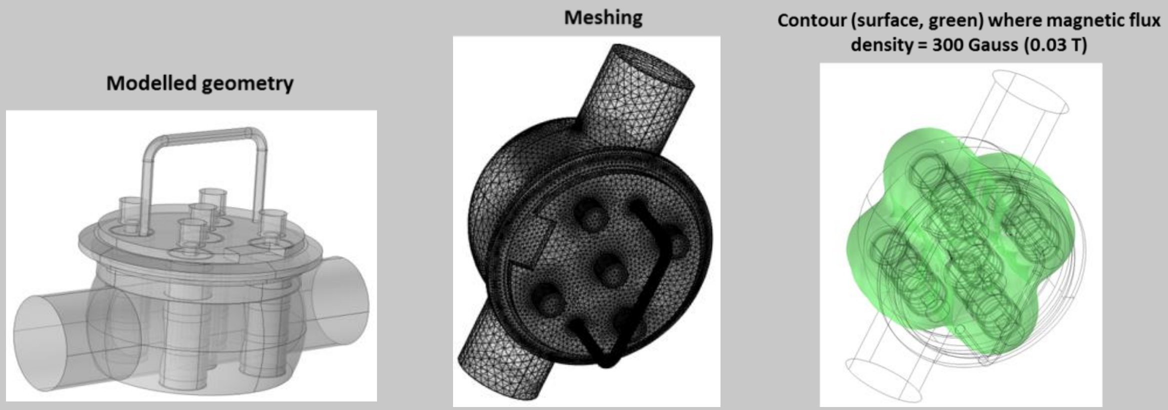
This filtering is required to (1) guarantee a good quality end-product, (2) to prevent damage to processing equipment and to (3) reduce hazards, e.g. fire hazards caused by sparks from the metallic particles. One or more separators may be found at a production line. The particles are removed by exploiting their magnetisability and the resulting magnetic force operating on them. The separability of the particles depends on the magnet design, the magnetic properties of the particles, the size of the particles and on the flow conditions (flow distribution, viscosity, …).

The particles are typically low carbon steel, austenitic stainless steel (like AISI316 or AISI304), iron, nickel or iron-oxide (for example magnetite). The magnetic permeability **μ** of these materials varies largely. This results in a large variation of particle separability, with e.g. low carbon steels (high **μ**) much more easily separable than austenitic stainless steels (low **μ**). The particle sizes are typically in the order of micro- to millimetres.

The separators that are most commonly used in the food industry are of the bar magnet type, where several bars are placed in the product stream to capture the particles, each one consisting of a number of cylindrical permanent magnets and low carbon steel (‘pole’) plates stacked on top of each other. Other separators are of the plate magnet or drum magnet type. The design of these magnets is such that the magnetic field around these - in terms of spatial distribution of the magnetic flux density - is optimised with respect to the particle separation efficiency.

The permanent magnets are typically made from Neodymium (NdFeB), which is of the rare earth type and which is currently the strongest type of permanent magnetic material (in terms of remanence $\mathbf{B}_r$). Other employed permanent magnetic materials are ferrite, AlNiCo and Samarium Cobalt. These come in various qualities with respect to magnetic strength, mechanical properties, temperature and corrosion resistance, and as such may each be optimal for specific operating conditions.

Modelling and optimisation of magnetic separation systems continued



FEM results for a magnetic separator.

At Goudsmit, FEM has been used to analyse and optimise magnetic separation systems, exploiting the multi-physics option of COMSOL to combine magnetic field calculations with flow calculations. After combining these calculations, paths of particles through the separator are computed, using the so called particle tracing option present in COMSOL, and it is determined whether these are captured by the magnet(s) or not.

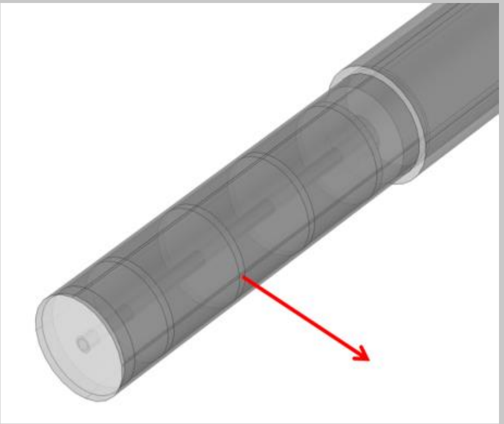
The particle tracing option uses Newton's second law and, consequently, employs a magnetic force expression (next to drag and gravity force) for computing the particle paths. It is noted that the magnetic force on a particle is proportional to the product of **B** and its gradient **∇B** [Sv04], i.e. the so called 'force index' **B ∇B**. Hence, magnetic separator design should not be focused only on maximising the size of the volume of the magnetic field with maximum **B**, as one might be tempted to think, but with maximum **B ∇B**. By feeding multiple particles to the separator under different conditions, for example at different entrance locations, and subsequently counting the number of particles that are captured an idea is obtained of the separation capability of the system.

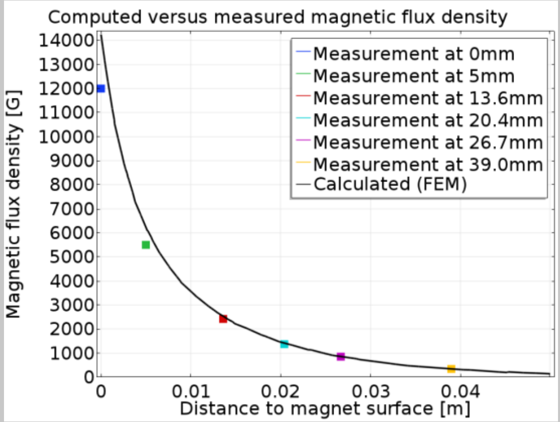
This FEM approach also allows for determining the effect of a.o. flow velocity, distribution and particle sizes on the separation efficiency. Optimisation parameters here include (i) the grade, location and layout of the magnets, (ii) the shape of the product flow volume and (iii) the shape and location of flow guidances.

Flow calculations also allow for making an estimate of the pressure drop over the separator. For some applications, especially for viscous product flows, a sufficiently low pressure drop is an important design objective next to a sufficiently high separation efficiency to minimise pump or compressor costs.
FEM results for a specific – 5 bar magnets based - Goudsmit magnetic filter under specific operating conditions (water flow, inlet velocity 1 m/s) are depicted in the figure on the left.

Modelling and optimisation of magnetic separation systems continued

One important research focus for Goudsmit in the field of magnetic separation is currently the modelling of powder flows, where particularly the potential of the so called Lattice-Boltzmann Method [GS18] is investigated in cooperation with the Eindhoven University of Technology and Flow Matters Consultancy BV.
Goudsmit also compares FEM calculations with measurements to validate and obtain confidence in these calculations. A bar magnet example of such a comparison is given in the figure below.



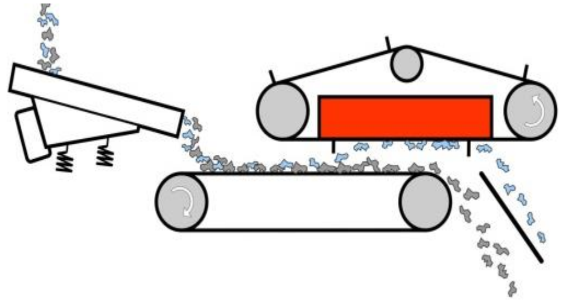


Measured versus computed magnetic flux densities for a bar magnet (distance along red arrow).

As can be observed, the computed flux densities follow the measurements quite closely. The difference becomes larger closer to the bar surface. It must be noted that close to this surface it typically becomes more difficult to measure the flux density and measurement errors are easily made.

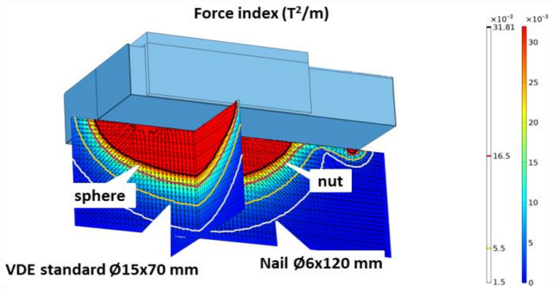
Recycling

A typical application in recycling involves a conveyor belt from which valuable metal objects are to be separated from other material by an overhanging – so called – overband magnet.



Recycling through an overband magnet.

These overband magnets may be of the (fully) permanent magnet or electro-magnet type. Either way, the quantity of most interest is the force index, in particular its distribution over space towards the conveyor belt. This is due to the fact that, as with the magnetic separators discussed above, the force on the object to be separated is a function of the force index. FEM calculations are used to compute this distribution. In the figure below you see the results from an electro-overband magnet.

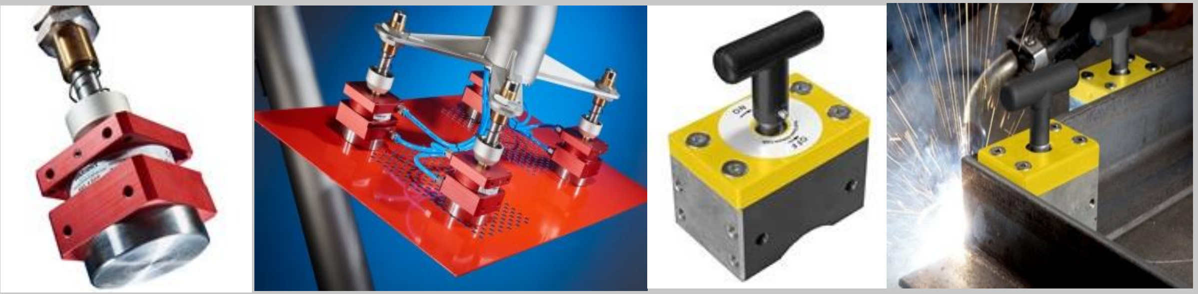


Test object	Force index [10^{-8} T^2m^{-1}]	Catch distance [mm]
Ball Ø 5mm	31810	310
Hex nut M4 (DIN934)	16500	400
Ø 15x70mm (VDE)	5500	540
Nail Ø 4.5x90mm	1500	720

The computed force indexes allow for estimating a catch distance for a specific object. Catch distances calculated for various objects are given in the table above as well and have been found to agree well with measured ones.

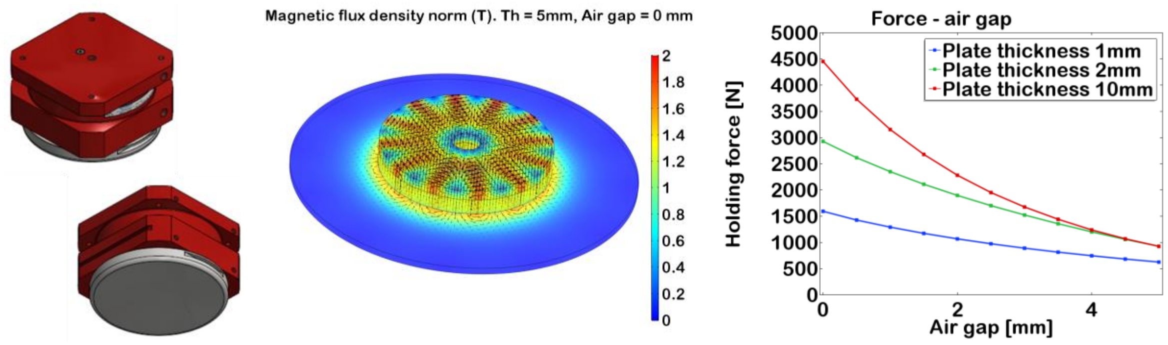
Magnetic handling

Magnetic handling devices are used to pick up, move and/or fixate ferro-metallic objects, e.g. plates. Some common devices are depicted in the figure below. Referring to their functionality, these have names such as magnetic gripper or end effector. Typically, these devices are equipped with the ability to switch the force on the object to be handled ON or OFF, which may be done either manually or automated (e.g. pneumatically).



FEM calculations are typically used to estimate the holding force on the object and determine the switching behaviour of the device. This force is computed through a surface integral from computed magnetic flux densities. Typically, forces are over-estimated and good practice is to allow for some ‘safety factor’ (<1) in force calculations.

As an example, results from an FEM force calculation are given in the figure on the right. These results are for a magnetic gripper, with the force between this device and a plate computed as a function of the distance, the so called air gap.



Force-air gap curve for an end effector, for various plate thicknesses

Note that the force drops off very quickly with increasing air gap. The holding force is defined as the force at zero air gap. The steep decrease in force as a function of air gap indicates that, even if one is interested only in the holding force, it is good practice to still take into account any possible nonzero distance between the objects of interest (e.g. due to surface roughness).

A recent more extreme handling application where FEM based forces have been used in the design process has been the magnetic mooring of a ferry. This project was done together with the Dutch company Mampaey Offshore Industries, with the magnetic mooring system aimed for handling ferries in London on the river Thames.

Magnetic mooring system: magnets in green circle.

The holding force for each one of the four pads in the green circle in the figure above must be around 80000N.

Magnet–Hall sensor combinations

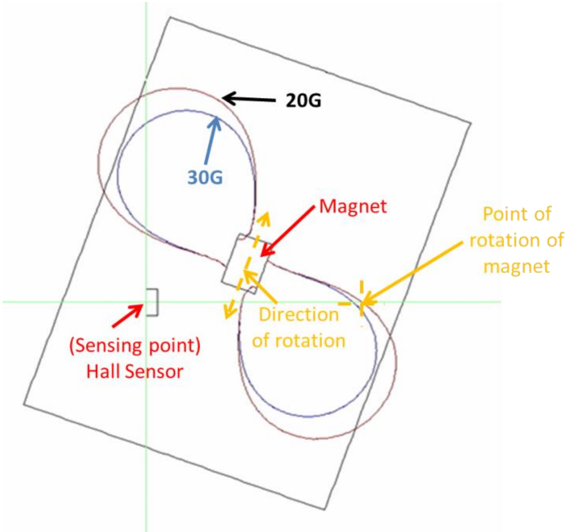
When a magnetic field is applied perpendicular to an electric current flowing through a conductor (with finite width), a voltage difference is obtained transverse to this current (along this width). This is called the Hall effect, and the resulting voltage the Hall voltage. See for example [Kr91]. A Hall sensor exploits this effect and translates a detected magnetic flux density into a voltage difference. As a consequence, a Hall sensor can be used to detect variations in the surrounding magnetic field and, thereby, to detect movement of a sufficiently nearby object when a magnet of sufficient strength is attached to this moving object. Such magnet-Hall sensor combinations can be found in many devices found in a.o. the consumer electronics and automotive industry.

FEM calculations are typically used to determine and optimise the detection performance of a magnet-Hall sensor system. Applications include the detection of the rotation angle of a lever, the counting of the number of rotations of a gear wheel and the automation of the (de)activation of a device connected to the sensor output. The magnets involved typically are of the permanent magnet type. Optimisation variables typically include magnet parameters, for example remanent flux density, the location of the sensor and/or magnet and the type of sensor. Optimisation may also involve the determination of the effect of uncertainties (e.g. tolerances) on the detection performance. Many sensor types are commercially available with widely varying characteristics.

Their output may be a signal that varies continuously with detected flux density, or may provide for example a two-level output with threshold values determining when the (voltage) output switches from one value to another. Magnetic flux density levels detected by the sensors are typically in the order of 1 to several tenths of mT. Typically, the dimensions of a magnet-Hall senor system (sensor, magnet, distance) are relatively small, i.e. in the order of millimetres to several centimetres.

FEM calculations for magnet-Hall sensor applications most often translate to magnetic flux density calculations at a single point, representing the main sensing area of the sensor, as a function of a movement parameter (translation, rotation). The resulting flux density – movement curve is then evaluated with respect to the sensor characteristics, which may then possibly lead to adaptation of some design variable.

A (2D) result from a (3D) magnet-Hall sensor FEM calculation is depicted in the figure below. Here, the Hall sensor will switch its output level when the detected magnetic flux density increases above a threshold value of 30G, and will switch back to its former output level when subsequently the flux density will decrease below a second threshold value of 20G. The aim of this application was to determine the rotation angles at which these level switches take place.



FEM results for a magnet-Hall sensor application: 20G and 30G magnetic flux density contours around a rotating magnet.

Conclusions

Finite-element modelling (FEM) is an increasingly important tool for product analysis, design and optimisation for a company involved in magnetics like Goudsmit Magnetic Systems. In this paper, a state-of-the-art of FEM for magnetic applications, as applied at a company like Goudsmit, has been provided. More specific, both the FEM method and a variety of applications of this method, as applied at resp. encountered at Goudsmit, have been discussed in more detail.

Applications that have been discussed are within the fields of magnetic separation, recycling, magnetic handling and Hall sensor based movement detection. For some applications it is not sufficient to only model the electro-magnetic phenomena but other physical phenomena must be taken into account as well, in particular the product flow in case of separation applications.

Literature

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More information about FEM calculations?

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

Youtube:

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

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