

Design and Optimization of Magnetic Systems with COMSOL® at Goudsmit Magnetics

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Abstract

A state-of-the-art is presented of the numerous COMSOL® finite-element-method applications at Goudsmit Magnetics, a Dutch vendor of permanent- and electro-magnetic systems. COMSOL® is used here for design, optimization and innovation of these systems, which does not only involve the finite-element-modeling of permanent and electro-magnetic phenomena alone, but also flow (computational fluid dynamics), (material) mechanical, heat transfer and particle tracing phenomena. Particularly the ability to simulate combinations of these phenomena is considered an important advantage of COMSOL® because of the multi-physics nature of many of Goudsmit's applications.

Keywords: Finite-element-method, COMSOL®, permanent magnets, electro-magnetism, computational-fluid dynamics, particle tracing, separation, recycling, handling, production automation, demagnetization, sensing.

Introduction

Founded in 1959, with headquarters in Aalst-Waalre, the Netherlands, and having approximately 140 employees, Goudsmit Magnetics is a specialist in the field of magnets and magnetism and delivers both standard and custom-made permanent and electro-magnet systems and services in various fields, of which the following are the main ones:

- *Separation*
Magnets are used here for the removal of unwanted small metallic particles from a product flow for reasons of e.g. health, safety and/or environment. An important market here is the food industry.
- *Recycling*
Here, too, metallic objects are separated with magnets from a stream, often a waste stream, but now with the aim to sell the collected material. The separated objects hence represent here a commercial value rather than a disturbing factor. Separate solutions exist here for recycling of ferro-metallic type materials, which are attracted towards magnets, and for recycling of non-ferrous, electrically conducting objects like aluminum and copper, which are repelled via time-varying rotating magnetic fields and the eddy-currents these induce in these objects.
- *Handling*
Most magnetic devices here are used to pick up and move, or to fixate (ferro-)metallic objects. These applications are typically used for the automation of production lines, for example in the manufacturing industry.

- *Applied Magnetics*

Here, the focus lies on stand-alone magnets and assemblies. One of the more common Applied Magnetics applications is *magnetic sensing*, where magnets are combined with magnetically sensitive sensors, like the Hall (effect) sensor, to detect e.g. on/off situations, open/closed situations, position, angle or number of rotations.

Finite-Element-Method (FEM) Modelling with COMSOL® [1] has been extensively used for many years at Goudsmit to answer system performance questions for the applications above, both from customers and Goudsmit colleagues and via projects ranging in size from fast testing of small new ideas to large scale product innovation projects. This has led a.o. to a considerable amount of standard FEM-COMSOL® work flows within Goudsmit Magnetics for various applications.

The main aim of this paper is to present an overview of the state-of-the-art of the COMSOL® applications at Goudsmit Magnetics. In [2] an earlier such overview has also been presented but here a significant amount of new developments and initiatives are included compared to this reference.

Goudsmit FEM applications

Magnetic separation

With a typical magnetic separator the fluid containing the particles to be separated is led through a magnetic field. This field exerts magnetic forces on these particles, which consequently are drawn to the

surface parts of the separator where the magnetic fields are strongest. The particles are regularly removed from those surfaces via a cleaning step, with the fluid flow through the separator temporarily halted. The fluid, often denoted as the *product*, can be gaseous, liquid or mixed solid-gas, i.e. a powder. The particles to be separated are typically low carbon (structural) steel or austenitic stainless steels like AISI316 and AISI304. Typically the separator is installed in a production line containing a pump or compressor that ensures flow over the magnetic filter, i.e. that has sufficient power (head) to overcome the encountered pressure drops over the separator.

Most commonly, the magnet field is created through magnet assemblies contained in tubes of stainless steel that are inserted in the product flow. See Fig. 1.



Figure 1. A typical tube type magnetic separator.

Other types of separators uses block or drum like magnet assemblies.

The magnet assemblies consist of permanent magnets (PM) and soft magnetic materials, typically of the structural steel type. The function of the latter may be summarized as to collect and conduct the magnetic flux produced by the PM's and to drive this flux in and out the product flow in a concentrated manner.

In tube type of magnet assemblies these soft magnetic materials create (N, S) poles on the tube surface, giving rise to their name of *pole plates*. Here, the magnetic flux densities are highest and, consequently, the particles are collected. Magnetic separator vendors typically aim to maximize the magnitude of the pole surface flux densities, also referred to as *the Gauss value*, and specify this value at Sales interactions, even though more factors play a role in the separation performance - like flow conditions and particle properties. Also, systems with a lower *Gauss value* may perform better than systems with a higher *Gauss value* due to e.g. a different magnet tube layout and configuration.

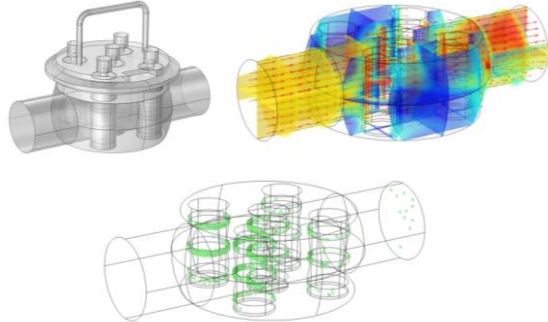
The focus with most Goudsmit FEM magnetic separator studies, for customers or internal to Goudsmit, lies either on (i) computing the magnetic field, on (ii) estimating the separation performance, in terms of percentage particles captured, or on (iii) providing an estimate of the pressure drop over the separator. The results may be used for e.g. new product development, system optimization, finding the optimal flow conditions, finding the optimal location along the production line, for quality check and auditing purposes, or for determining a safe distance from the device from a pace maker user point of view.

For estimating the separation performance of magnetic separators, Goudsmit exploits the ability within COMSOL® to combine physics domains of different nature. More specific, we combine modelling of magnetism (Maxwell's equations - AC/DC), flow (CFD - Fluid Flow) and particle tracing (Newton's second law) for that purpose. First, the magnetic field in the separator is calculated, using a.o. known magnetic properties from the magnets and poles (hysteresis-curve approximations). Secondly, the flow properties are calculated, providing a.o. the velocity distribution over the separator. Finally, particle trajectories are calculated assuming the particles to be subject to magnetic, drag and gravity forces. For this final step, the results from the magnetic and flow field computation steps are used.

See Fig. 2 for results from a COMSOL® FEM study on the separation performance of a Goudsmit separator [3]. Shown here are results from velocity distribution calculations and particle tracing. The green dots here are particles that have been captured on the tubes around the poles. By counting those particles and comparing those with the number of particles that were specified to enter the separator, the separation performance is estimated. See the table for results, where one can clearly see the influence of magnet strength, particle material and particle size on the separation performance.

Pressure drop studies are less time consuming and require only the CFD flow step discussed above for the workflow for estimating the separation performance. The resulting pressure drops are then used to determine whether the pump or compressor in production is properly rated, or that maybe another filter must be chosen with smaller pressure drop. For the latter, one may even consider a separator where the fluid is heated to reduce its viscosity. This may not only reduce the pressure drop but may also considerably improve the

separation performance. Such heating may, for example, be applicable for chocolate flows.



Magnet material & grade	Remanence (T)	% Particles captured (of those entering the filter)					
		AISI316 D=1mm	AISI304 D=1mm	LC steel D=1mm	AISI316 D=0.1mm	AISI304 D=0.1mm	LC steel D=0.1mm
Ferrite F47	0.46	38.1	65.2	100	8.0	22.6	100
Neodymium N35	1.17	50.2	96.6	100	12.3	68.0	100
Neodymium N52	1.42	51.7	98.9	100	13.3	77.1	100

Figure 2. COMSOL® FEM computation of the separation performance of the Goudsmit E0016970 filter for water product flow entering the filter at 1m/s, and for various magnet strengths/materials, particle materials and particle diameters.

The Goudsmit COMSOL® FEM workflows for estimating the separation performance and pressure drop are relatively mature for Newtonian liquid and gaseous product flows. See [2] for more details. A recent new development is the usage of *non-Newtonian* fluid models. In particular, a recent study involved the COMSOL® Bingham-Papanastasiou viscosity model for simulating a magnetic separator application in the upstream oil and gas industry, a relatively a-typical application for Goudsmit. Another new development is that of usage of powder flow simulations where the powder is assumed to be homogeneously distributed over the fluid. This homogeneous distribution is enforced during the simulations, where the Euler-Euler Model physics option was used for multi-phase flows. See Fig. 3 for an example COMSOL® FEM simulation result.

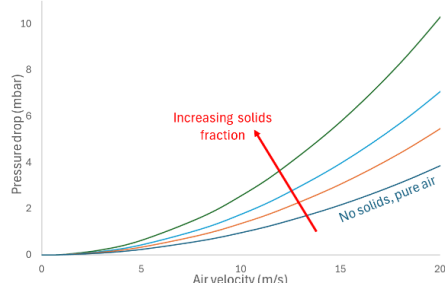


Figure 3. Homogeneously distributed powder flow pressure drop calculations for a Goudsmit magnetic separator, as computed with COMSOL®.

Simulation of powder flow has been, and will likely be, a challenge for Goudsmit for many years, while at the same time being of high importance because

of the many applications encountered at Goudsmit with this type of fluid. Part of the challenge lies in the wide variety of powder flow types and related physical aspects. Focus point of research in powder modelling at Goudsmit has not only been the implementation in COMSOL® but also to consider an alternative approach using the so called Lattice-Boltzmann Method [4], which application has been investigated in cooperation with the Eindhoven University of Technology and Flow Matters Consultancy BV [5]. Another, new, research direction is the modeling of *rotating* separators, i.e. where the tubes are rotating around. Goudsmit sells such equipment for example to prevent powders to stack up in piles on the tubes to, thereby, hinder the migration of particles to the tube poles. Finally, a new research direction is that of modelling the agglomeration of particles due to inter-particle magnetic forces. This may result in – effectively – larger particles and, thereby, an improved separation performance. One may even add magnetic particles to the fluid to stimulate agglomeration. Inter-particle forces are currently not present in the Goudsmit separator models.

Recycling

Recycling has two components: re-gaining of (i) ferro-metallic materials, like structural steel, through attractive magnetic forces and of (ii) electrically highly conducting materials - like aluminum and copper - through induced Eddy-current induced repelling forces. Correspondingly, Goudsmit has been working on the development COMSOL® FEM models for both these components.

The separation of ferro-metallic materials through attractive magnetic forces typically is done with either drum, head roll, block or *overband* magnets. The latter are magnets hanging over a conveyor belt over which the valuable metal objects are transported, together with other materials from which these are to be separated. See Fig. 4.

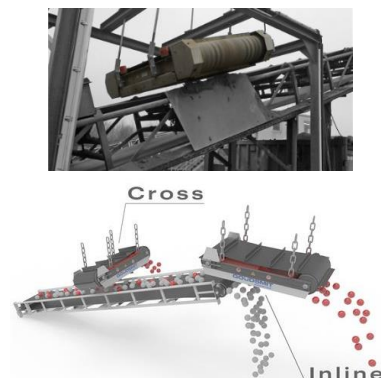


Figure 4. Recycling of ferro-metallic materials through an overband magnet

COMSOL® FEM studies for these attractive force based ferro-metallic recycling systems focus on computing the spatial magnetic flux density distribution and the so called *force index*. This quantity is computed as the product of flux density and its gradient. It is of most interest for recycling systems because both the magnitude and direction of the magnetic force on any ferro-metallic object is a function of this product. A typical FEM result for an overband magnet is a 3D force index magnitude field, together with an estimate of the catching distance of some objects for which the force index required to attract it from the belt are known, as exemplified in Fig. 5. This information provides e.g. an idea about the height with which the overband magnet should hang over the belt to be effective.

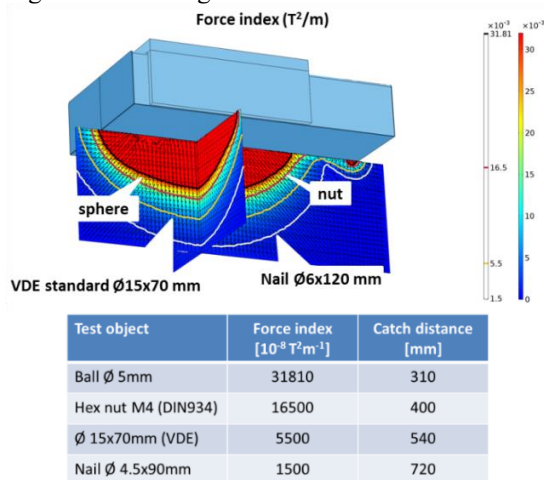


Figure 5. FEM force index and catch distance calculations for a Goudsmit electro-overband magnet.

Whereas the COMSOL® FEM workflows for the drum, head roll, block and overband magnets are mature, that of eddy-currents based recycling equipment is still under development. This particularly applies to time domain simulation of the objects to be separated for eddy-current systems of the type displayed in Fig. 6.

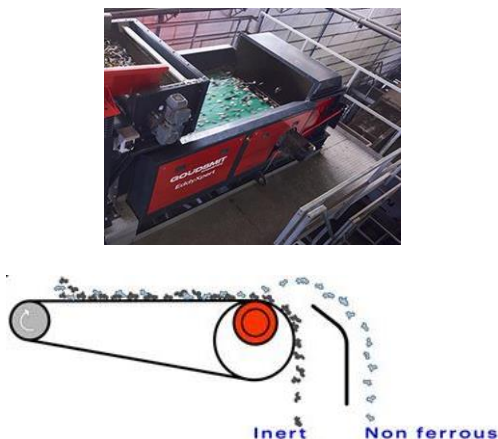


Figure 6. A typical Goudsmit eddy-current separator.

For these eddy-current recycling systems the non-ferrous, electrically conducting materials are spread out over a conveyor belt, together with the remaining non-conducting – *inert* – material. The belt then transports these materials to and over a fastly rotating magnet roll. This induces eddy-currents and repelling forces in the electrically conducting materials which, consequently, are thrown of the belt further away than the inert material, and over a carefully placed divider plate.

Time domain simulation of eddy-current recycling systems, which mainly vary in role and magnetic configuration parameters, is believed to be beneficial for Goudsmit because it allows for a relatively quick and cheap performance assessment, optimization and design of these systems. It may particularly allow for a large reduction in relatively costly (physical) experimentation time. An example of a COMSOL® FEM time domain simulation result for a Goudsmit eddy-current recycling system, is given in Fig. 7.

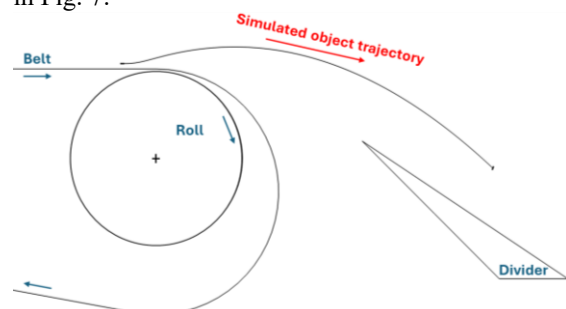


Figure 7. FEM computation of the trajectory of an object being launched from a conveyor belt due to eddy-current induced forces.

Magnetic handling

Magnetic handling products at Goudsmit cover a wide range of products which have magnetic force based manipulation of objects in common. This force is e.g. used to (i) pick up and re-locate an object, for instance one or more steel plates, cans or glass jars with steel lids, (ii) to temporarily keep an object fixed at a location, e.g. along a production line, or e.g. (iii) to separate stacked sheets of plate material from each other. An important group of products is that of the *grippers*. 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. The latter allows for easy integration in - and automation of - production lines. The automated switching can be done e.g. pneumatically or, as a recent Goudsmit development, electr(on)ically. The latter grippers are also called *e-grippers*. Another handling product is e.g. the *sheet separator*, where metallic sheets are separated via the principle that alike poles (N – N or

S – S) repel. *Palletizers* lift a layer of many objects (cans, jars) in one go and allow e.g. for automation of packing or un-packing processes. For most handling devices a PM based and an electro-magnet based version exists. A few Goudsmit handling devices are depicted in Fig. 8.



Figure 8. Goudsmit magnetic handling systems.

Goudsmit COMSOL® FEM work for its Handling systems largely focuses on computing magnetic forces on objects. More specific, the COMSOL® AC/DC module is often used to find out what this *holding force* on the object to be lifted is for zero and larger distances between gripper and object. This distance is also known as the *air gap*. See Fig. 9 for examples of computed *force – air gap* curves, computed for a Goudsmit gripper type device that needs to lift a steel plate. Note the dependency of the force on the plate thickness. For smaller thicknesses magnetic saturation effects come into play, which reduce the force. Note also that the force drops off very quickly with increasing air gap and that, hence, this is an important parameter too to take into account in gripper evaluations, selection and design.

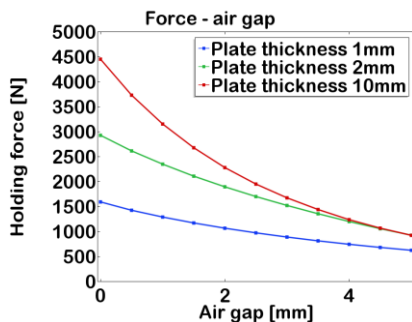


Figure 9. Force-air gap curves for a Goudsmit gripper to lift a steel plate, for various plate thicknesses, as computed with the COMSOL® AC/DC module.

Force - air gap curves are also determined through testing and then compared to their FEM computed counterparts. This provides both validation of - and confidence in - the FEM models and a *safety*

(compensation) *factor* to reckon with when using only computed curves for evaluating a gripper.

COMSOL® is also used to determine how many plates of a stack can be lifted, or how many grippers are needed to lift an object.

An interesting, somewhat atypical and extreme example of a Handling product for which COMSOL® has extensively been used in the design process has been the magnetic mooring system for a ferry on the river Thames in London. This project was done together with the Dutch company Mampaey Offshore Industries [6]. See Fig. 10. The holding force for each one of the four (black) pads in this figure was around 80000N.

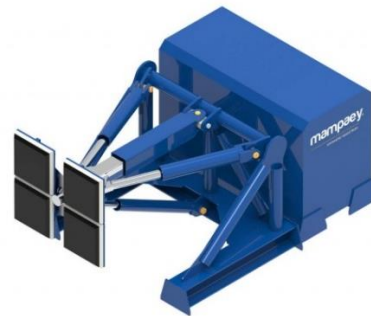


Figure 10. Magnetic mooring system: the magnets are located in the four black pads shown in the upper figure.

Another application that formally falls within the Goudsmit Handling portfolio is that of *demagnetization*. The corresponding devices are used to remove undesired rest-magnetism in materials. Such remanent magnetism may e.g. disturb welding of pipelines. Demagnetization devices use coils and time- and amplitude varying currents to demagnetize material to a sufficiently low level (typically in the order of 1–10 Gauss). The coils create magnetic fields that apply torques on an atom and molecule level that allow for the demagnetization of the material at hand. COMSOL® is used here for coil geometry, magnetic field, material penetration depth and heat production computations.

Applied Magnetics

An important Applied Magnetics application for Goudsmit involving COMSOL® FEM simulations has been that of magnetic sensing, in particular those involving *Hall (effect) sensors*. These sensors exploit the fact that electric currents are subject to (Lorentz) forces when placed in a magnetic field, and use this fact to transform the sensed magnetic field into a proportional voltage signal. This type of sensor has found widespread use in industry in combination with a magnet for applications involving contactless proximity sensing, position and speed detection, e.g. in automotive systems and consumer electronics. The magnet, typically a PM, is then contained in the moving part while the sensor is contained in the stationary part, or vice versa, and the output electric signal of the sensor changes as a function of the distance between magnet and sensor.

For many magnet – Hall sensor applications, Goudsmit has applied COMSOL® FEM simulations to determine the feasibility of these combinations, and/or to re-design these in terms of magnet strength, dimensions, magnet-sensor distance and relative location. Often, but not only, these applications involve Hall sensors where the electric output changes from one level to another when the sensed magnetic flux density value exceeds or undershoots a threshold value.

Magnet – Hall sensor combination simulations for Goudsmit’s applications typically involve computing the magnetic flux density at the (actual sensitive location within the) sensor as a function of the movement of the magnet. At first, for Goudsmit, these simulations involved computations for *nominal* (average/median) design parameter settings only. See Figs. 11 and 12 for corresponding COMSOL® FEM simulation results.

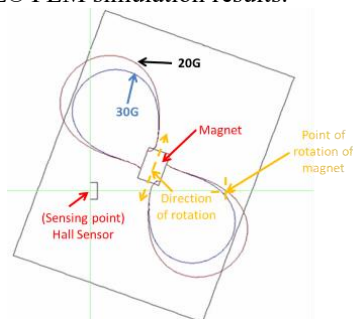


Figure 11. COMSOL® FEM results for a rotating magnet-Hall sensor application: 20G and 30G magnetic flux density contours around a rotating magnet.

Fig. 11 depicts a 2D result from a 3D magnet-Hall sensor FEM calculation. 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 switchings take place.

Fig. 12 depicts a typical flux density-magnet movement relation computed with FEM under nominal parameter settings.

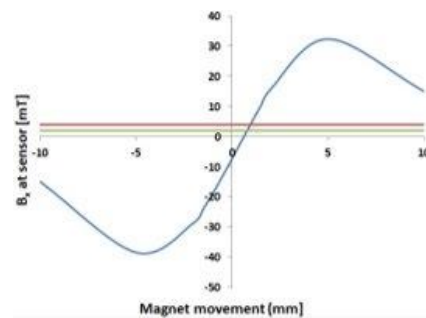


Figure 12. Magnetic flux density component (B_x) detected by a Hall sensor when a PM moves along a straight line and passes this sensor at a certain distance, as computed with COMSOL®. Also, in red and green, the switching threshold values of the considered Hall sensor are shown.

More recently, customers have indicated to Goudsmit to look for a more in-depth analysis involving also the *tolerances* on the magnet-sensor design parameters, such as e.g. magnet dimensions and relative location. Taking only the nominal design parameter values into account may still lead to numerous failures in practice while/ even though the nominal performance was analysed to be well. Taking a *robust* design approach, with explicit consideration of the design parameter tolerances, we can largely reduce this failure rate. This can e.g. be established by narrowing the manufacturing tolerances to be fulfilled on critical such parameters, as identified during the robust design approach.

The Goudsmit robust design approach to PM – Hall sensor combinations is effectively a brute force and worst case approach involving numerous simulations at the limits defined by the tolerances. However, to avoid simulation of *all* possible limit situations, a clever selection in simulated cases is made based on physical insight, thereby reducing the overall simulation time and memory storage to an acceptable level. See also [7]. Fig. 13 shows an example FEM result obtained with this approach. Note that, due to the uncertainties introduced by the tolerances, for one magnet location the sensed flux density now may vary over a *range*, rather than being a single value. The same applies to the magnet movement values where the sensor threshold values may be crossed.

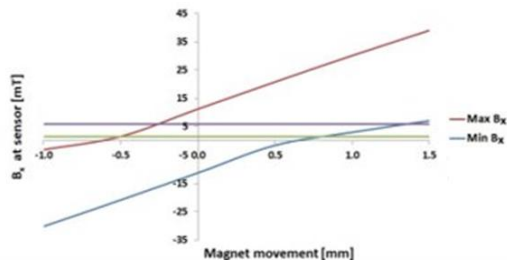


Figure 13. As for Fig. 12 but now taking all possible design parameter variations into account as specified by corresponding tolerances.

Other Applied Magnetics applications at Goudsmit involving COMSOL® FEM computations have been a.o.:

- *Eddy-current damping systems*
Here, eddy-current induced magnetic forces are used to dampen the motion of a moving system by letting this motion be accompanied by the motion of a magnetic field through a conducting material.
- *Contactless force or torque transfer systems*
A first example here is a system of two rotating discs where one disc must make the other one rotate as well through a contactless magnetic torque connection. Another example is where a piston in a tube must be moved without a rod by a moving device outside the tube that is contactless connected with this piston through a magnetic force. A final example is that for a contactless magnetic force based gravity compensator.
- *Wireless power transfer systems*
This involved coil computations, and no PM calculations.
- *Mass spectrometers*
Here, for the purpose of identifying the composition of a material, this material is first ionized, after which the ions are accelerated in an electric field and then fed to a magnetic field. This magnetic field causes the trajectories of the ions to bend to known locations where the particles are collected for counting.
- *Magnetic bearing*
- *Magnetic plates for planar motors*
Such motors are used in the high-tech industry.
- *Switched reluctance electro-motors*
- *Magnetic shielding systems*
- *PM magnetic moment computations*
Measurement of magnetic moments of PM's are done relatively easy and are used for PM quality checks. FEM computations here are typically used to provide an acceptable lower or upper bound on the measured magnetic moment.

It may be clear that there is a large variety and versatility in the applications here.

Finally, we would like to note that Goudsmit has also been involved in Hyperloop initiatives over the years, both commercial and at universities [8, 9], where magnetic systems play an important role, for propulsion, lifting, stabilizing and braking.

Conclusions

Finite-element modelling, in particular through COMSOL®, has been and will be an important tool for product analysis, design, innovation and optimization for Goudsmit Magnetics. In this paper, a state-of-the-art of the FEM applications at Goudsmit has been given, including some new developments therein. Applications that have been discussed are within the fields of magnetic Separation, Recycling, Handling and Applied Magnetics, which are the dominant application areas for Goudsmit. The variety in applications is large. Also, often, multiple physics domains – such as magnetism, flow and particle tracing – need to be combined. It is considered an important advantage of COMSOL® that it allows for this combination.

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