A Hands-on Experiment for Empirical Validation of EMS Magnetostatic Analysis

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Abstract—**This paper focuses on the development of a practical teaching activity for undergraduate students evolving in the engineering field at École de Technologie Supérieure. A simple and portable experimental setup is proposed around the measurement of a force through a transducer connected to a NSpire CAS calculator manufactured by Texas Instruments. This activity consists of an empirical validation of the axial force generated by a diametrically polarized magnet. The bench is composed of ferromagnetic material, neodymium magnet and force sensor. Presented as an introduction to Finite Element methods, students are first invited to model each important part with SolidWorks. Then EMS is used to model & match by simulation the magnetostatic apparatus. From the results obtained, students are guided to build confidence in the use of the software. This document mainly focuses on academic and learning points of view, and shows how EMS can be a great tool for helping students to grasp electromagnetic «complex & invisible» phenomena.**

Index Terms—NSpire calculator, hands-on experience, neodymium permanent magnet, diametrically polarized, finite element method, magnetic flux, force sensor, caliper measurement

I. INTRODUCTION AND MOTIVATION

THIS paper describes the development of a hands-on activity. In the context of teaching a multidisciplinary project, students of different disciplines have to work together to meet a "not so easy to reach" goal. In this case, it will be a mechanical bird.

Figure 1. A mechanical bird is called an ornithopter

In this kind of project, we expect students to build everything that is not provided to them. One aspect of the challenge related to this ornithopter is to build the motor from scratch based only on the tube form NdFeB permanent magnet shown in Figure 2.
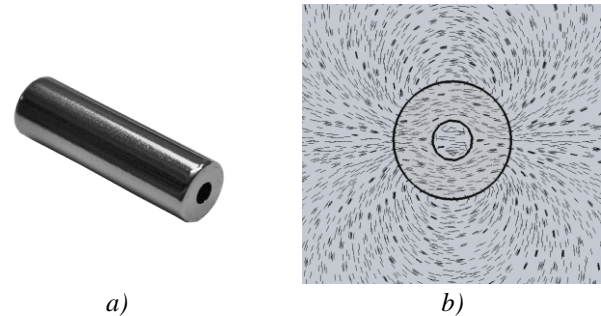

a)   *b)*

Figure 2. a) Grade N50 neodymium (NdFeB) permanent magnet with dimensions (ID = 2mm, OD=6mm, Length=20mm); b) Magnetic field lines (axially cut view section)

The provider [1] of the magnet just gives the information about the grade of material used that is N50. This magnet is especially chosen for his diametrically polarized configuration intended for motor built purposes. As shown in Figure 2a, this means that instead of being magnetically polarized axially (along the axis of rotation of the tube), this magnet is polarized against its sides.
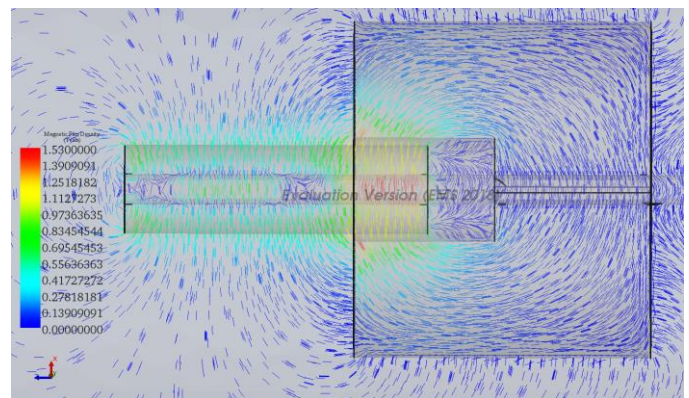

Figure 3. Cut view of diametrically polarized tube magnet partially inserted inside a ferromagnetic cylinder with a hollow space.

This configuration allows the making of a simple brushless DC motor (Figure 4) in which the brush commutation is realized by specialized chip [2] that analyzes magnetic field position with a built-in Hall effect sensor and commute electronically the direction of current feeding to the wounded coil by an integrated H-Bridge.
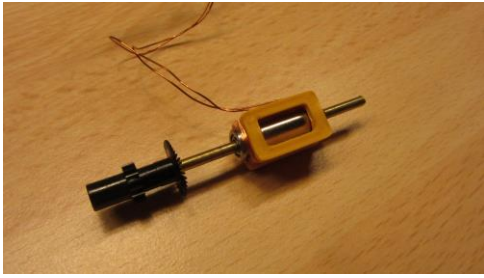
Figure 4. Example of brushless DC motor exploiting a diametrically polarized permanent magnet

To achieve the design of this type of simple form motor, each team has to (beside, determining gauge of wire, number of turn to wind, and take in account current limitation of the chip, mechanical friction reduction, …) start their design around a yet unknown characteristic: the magnetic flux value of the magnet (in Weber). To get this value, three different approaches will be explored, namely: *Analytical*, *Numerical* & *Experimental*.

II.   APPROACH FOR SOLVING PROBLEM IN ENGINEERING

An simple *analytical* approach can be expressed as follows, a magnet with a material Grade of N50 is reputed to present a magnetic flux density (Br) of 1.42 Tesla [3]. We teach that magnetic flux density is related to flux density by surface crossed by the flux. Analytically stated as,

$$\Phi = B \cdot A$$

Where Φ is the desired magnetic flux [in Wb], B is the magnetic flux density provided [in T] and A is half cut side tube area of the magnet [in m^2]. By substituting with values related to this geometry, we can estimate the flux Φ to be about 268 µWb for external surface down to a value of 114 µWb for internal magnet cross-section area, if we split it in half. As we will note later, this analytical approximation is a little off-road and should not be blindly taken as starting point for any serious design attempt.

The *numerical* approach is performed through the use of an Electromagnetic simulation environment based on Finite Element methods. Because we are involved with SolidWorks as CAD tool for all mechanical modeling of the project, it is obvious to opt for the EMS module specially integrated with this CAD software. Like any new software to which someone is exposed for the first time, confidence has to be built on how to operate it and then can begin its mastering. That's why some proof of concept has to be performed before serious trust is established.

This is not yet the case for our students for whom this is their first contact to the finite element method and it poses its own challenges. So it is not advisable to let them just model the magnet alone and let them trust any result that the software will throw without any possible way to counter-verify them. This is why we want to establish a match with experimental results.

 The design of the *experimental* setup has to be cleverly designed by teachers to: minimize the material needed, maximize the robustness of the measurement results and be easily maintained by technicians in charge if any failure occurs.

In the past, with the use of dedicated analog hall effect sensor methods, like measuring magnetic field strength was utilized (which decrease in intensity as distance increase from the

magnet pole). We found that this kind of setup was prone to measurement error and typically characterized by a high sensibility to setup rigidity and nature of the surrounding material. This previously used approach was shown not to be reliable enough between even two wanted identical setup.

III.   DETAILS OF THE EXPERIMENTAL SETUP

Nowadays, force transducers are more available and affordable. Those sensors connected to the bachelor's degree required calculator allows users to perform neat data acquisition. This way, the measurement results can be easily read and shows to be more repeatable from one setup to another.
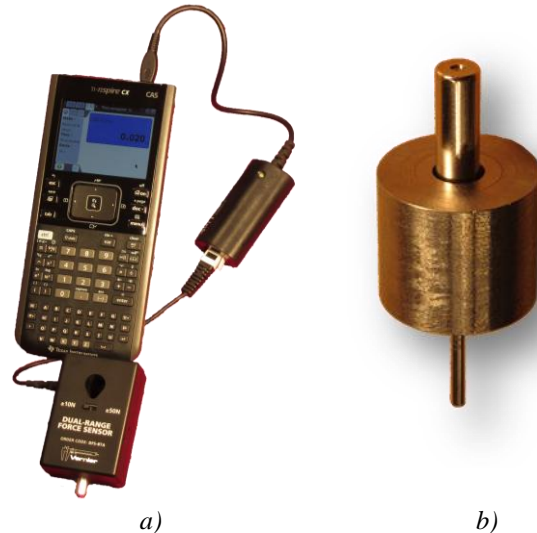

a)   *b)*

Figure 5. a) Dual-Range Force Sensor plug in the NSpire CAS Calculator; b) HMM & HFMC key setup parts

Figure 6 shows the experimental setup configuration. This setup is composed of a tube magnet press-fitted on a high-speed steel (HSS) rod free to slide inside a guiding hollow cylinder of ferromagnetic material (Soft Iron). Also, an ABS plastic holder (the orange part) has been manufactured on a rapid prototyping 3D additive type printer (of brand Zortrax M200) to hold together the moving parts over the sensor.
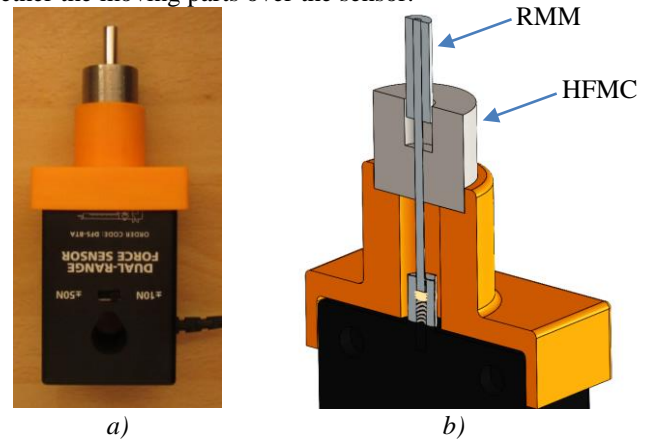

a)   *b)*

Figure 6. a) Picture of the real full assembly; b) Sectional view that shows the internal layout

Naturally, once the rod is inserted in the guiding hole inside the HFMC (see section IV), the magnet wants to slide downward because of magnetic attraction and the rod can

transmit this pulling force on the other end beneath the sensor stick. A little inner brass screw found inside the sensor stick can be adjusted to modify the excess length of the magnet over the HFMC.

IV. CONDUCT OF THE HANDS-ON ACTIVITY

The first step for students about this hands-on activity is to take the measurement of the two key part of the setup, namely: the Rod Mounted Magnet (RMM) and the Hollow Ferromagnetic Machined Cylinder (HFMC). For the RMM, four measurements has to be captured by the uses of a non-ferromagnetic caliper [4] : length & diameter of rod and magnet. The reason behind the use of a special caliper is because of the intense magnetic field that could otherwise damage the magnet. On the HFMC side, five measurements have to be performed by the use of a classic steel caliper [5]: outer diameter, overall length, depth and inner diameter of the hollow hole and finally the rod guiding hole found underneath the part. A special thoroughness has to be taken by students regarding the measurement of the inner hollow hole diameter, because any error on those measures can lead to a rapid offset in simulated resulting force. Also note that the rod guiding hole is narrow. It can be measured by talented students or be presumed at 2.04mm.
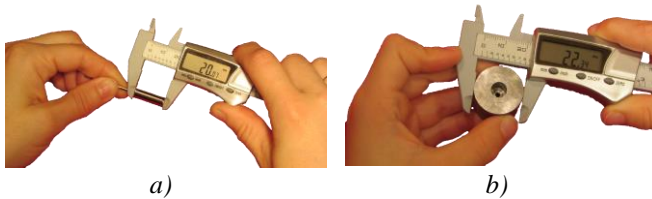

a) *b)*

Figure 7. (a) Magnet related dimension are captured using a carbon fiber digital caliper and (b) a standard steel caliper is used otherwise

Once all measurements are accomplished, it's time to create a model in SolidWorks. Fillet on edge of the magnet and other second order detail can be neglected for this first approximation of the apparatus.

	RMM	HFMC
	Dimension [mm]	Dimension [mm]
Length	20.04	19.63
OD	5.88	22.26
ID	2.00	6.89
Hollow Depth	-	9.30
Hole ID	-	2.04
Rod Length	54.33	-

Tableau 1. List of dimensions

V. SIMULATION RESULTS

At this point, three prerequisites are mandatory before starting to use EMS. Firstly, related constraints between parts has to be defined to make the setup look like Figure 8. Secondly, add to the assembly a cylindrical Air Volume that must surround all the parts. Learning by this very fact, the really useful stamp function available in SolidWorks. Thirdly, if not already done, students have to activate the EMS module found under Complements inside SolidWorks.

Then, with the use of the EMS tab, they can declare a Magnetostatic study on this enhanced assembly.

They are guided to assign particular material to each part of the assembly depending on the specific nature of each of them as listed in Tableau 2.

	Material type	EMS names (from library)
Magnet	NdFeB N50	perm. magnet/NdFeB/N5214
Rod	HSS Steel	non-linear/Typical Steel
HFMC	Soft Iron	Ferromagnetic/Iron

Tableau 2. List of assigned material

A special attention has to be paid to the magnet. Student have to assign the magnet coercivity. That is the magnetic polarization direction, which is sideway for this magnet (as reported in Figure 2b and Figure 3).

Progressing about the simulation setup, the meshing is the next step they perform. It is explained to them as an algorithmic process which cut each part (Air, RMM, HFMC, etc) into small interconnected pieces called domains inside which physical rules will be solved with consistency goal in mind. From the student's point of view, this slicing process will be kept somehow abstract and mysterious, but this is justified by their high level uses of the FEM. That's why, at this time, we will not give too much importance to the "under the hood" mathematics related to it. Default proposed meshing value are simply used.
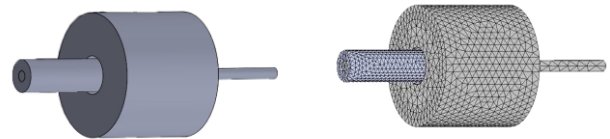

Figure 8. Meshing of the SolidWorks sensitive part into EMS with default proposed values.

Now everything is ready to launch the simulation by using the **Run** command. The force generated on RMM by the setup is reported under **Results→Results Table→Fz**. Simulation result can be compared to experimental result like the ones reported in Figure 9.

Students are made aware of the fact that the magnet has to be split in two for the coming purpose of measuring the magnetic flux in EMS.

The magnetic flux is deduced by EMS from the calculation of magnetic density flux crossing a surface by the **Results→Flux→Compute Flux** item found in EMS tree. The surface has to be chosen to be essentially perpendicular to the direction of the magnetic field. Here is why a direct cross-section of the magnet is involved. The Figure 6b give a sneak peak of the two sections areas on the magnet that must be selected to get a representative value of the wanted magnet magnetic flux.

Also for experimental relevance concerns, students are made aware of the effect of gravity that can bias the force sensor depending on setup orientation, which would affect in the same way any typical bathroom scale. That's why some care has to be taken about setting the force sensor in a right and fix orientation before performing the tare in the calculator.
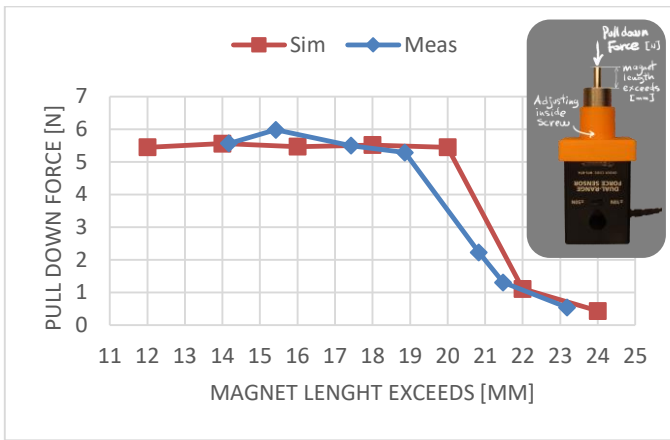
Figure 9. Force exerted on sensor by varying the position of the magnet through the means of the dedicated adjustment screw

Contrary to the seven points scan shown in Figure 9, students would just have to perform a single experimental measurement, as long as the magnet position is within the range of 14mm to 19 mm. Also, the premature down kink observed on the measure curve against simulation can find its explanation in the fact that simulation does not take yet into account the small fillet found on magnet edges because we intentionally did not include it in the model initially to keep it as simple as possible.

VI. DISCUSSION

From the Figure 9, we observe that the simulation matches very well the experimental measurement. An interesting observation is that the magnet really acts like a constant force spring (attracting itself downward with almost the same force whatever its position) as long as it is not near its limit border (far enough from bottom and not already outside over the HFMC). Figure 10 shows that the generated force is concentrated at the junction of the immersed magnet and the HFMC. This explain visually that once the magnet is immersed inside HFMC, only the magnet sidewall magnetic field found over the HFMC generated a force. Otherwise once the part of the magnet inside the HFMC, the sidewall magnetic field force cancel each other within the magnetic close circuit form by the HFMC.
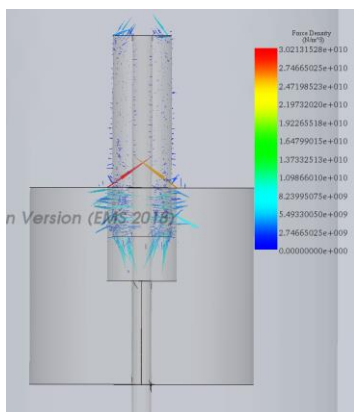

Figure 10. Force distribution vectors on a transparent side view for the generated downward pulling force (red/orange arrows) propagated by the rod mounted magnet that attracted inside the hollow ferromagnetic cylinder.

Students can also be introduced to some surface control leading them to better understanding that it can help to enhance results precision at a cost of higher computational effort & time consumption. Same idea can by apply about model fidelity, by adding fillet to magnet edges.

VII. CONCLUSION

A hands-on activity that introduce students to finite element method applied to electromagnetic is proposed. Calculating the magnetic flux of a magnet by the means of different approaches promoted for engineering, students build confidence in a simulation tools like EMS operated from SolidWorks. This activity helps them to develop skill with some measurements tools like caliper and controlling a finite element software. Once the model is reproduced inside SolidWorks, students are step-guided in performing a simulation which reveal the forces acting on the real experimental setup. Even if force values coming from both sources match well, numerical simulation provides a better estimate of a magnetic flux than the one provided by the analytical approach. Here, a value around $65\mu Wb$ has been found for the magnetic flux and that value can be used as a starting point design parameter for the construction of a homemade BLDC motor.

Future work would be to ensure that the characteristic of the applied materials fit the real ones. Also, we will look for a way to reduce the friction between the HMM and the HFMC and this way improve the reproducibility and reduce some randomness linked to manipulation.

And finally, it would be useful to perform a set of parametric studies to change material, key dimensions or surface mesh control and check how they affect the results.

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