A C.A.E. Tool to understand Magnetostatics

F. Buret, D. Muller, A. Nicolas, L. Nicolas
CEGELY - UPRESA CNRS 5005
Ecole Centrale de Lyon - BP163 - 69131 Ecully cedex - France

Abstract-- **We present in this paper a Computer Aided Education package allowing to visualize the magnetostatic field in and around the magnetic circuit of a double-U shaped contactor. The modeling of this device is performed by solving in real time a non-linear finite element problem. The implementation of this method is optimized greatly in order to allow to animate field patterns in real time in reaction to any user interaction. An evaluation of the improvements brought by this technique to the learning capabilities of students is presented.**

I. INTRODUCTION

The package *Contact* described here is used by students in engineering at Ecole Centrale de Lyon, in conjunction with an introductory course to electrical engineering. The objective of *Contact* is to allow the students to intuitively understand how the magnetic field arranges inside a magnetic circuit when varying parameters such as the inductor current, the number of turns of the inductor coil, the airgap width, and even the material characteristics. *Contact* takes into account the non-linearity of the materials, and enables therefore to study the influence of the saturation of the magnetic circuit.

The main problem when designing this package was to give an instant feedback to any interaction with the student [1,2]: in other words, any modification of a geometric, electric or magnetic parameter has to induce in real time a modification of the displayed results. The mathematical model used to get the distribution of the magnetic field is computed with the finite element method (F.E.M.), because of the possible non-linearities. Great optimization of its implementation then enabled a real-time solving.

We describe in a first part the studied device, the results that the students visualize, and what they are supposed to understand. In a second part, we present how we used the 2D magnetostatics F.E.M. in order to compute the distribution of the magnetic field in real time. We describe then the practical work that the students have to perform. Finally, we show how the pedagogical efficiency of the package has been analyzed.

II. OBJECTIVES AND VIEW

The studied device is the magnetic circuit of a double-U shaped contactor (Fig. 1). The magnetic field is created by one or two DC coils located on each arm of the contactor. Because of the large depth of the device, 2D approximation can be made.

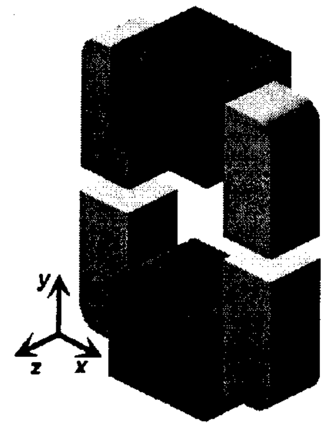

Fig. 1. Geometry of the magnetic circuit of the contactor.

Using the corresponding arrow buttons (Fig. 2), the user may modify geometrical parameter (the airgap), electrical parameters (the current and the number of turns of both coils) and magnetic parameters (the relative permeability at the origin of the B-H curve, and the flux density at saturation for both arms of the contactor).

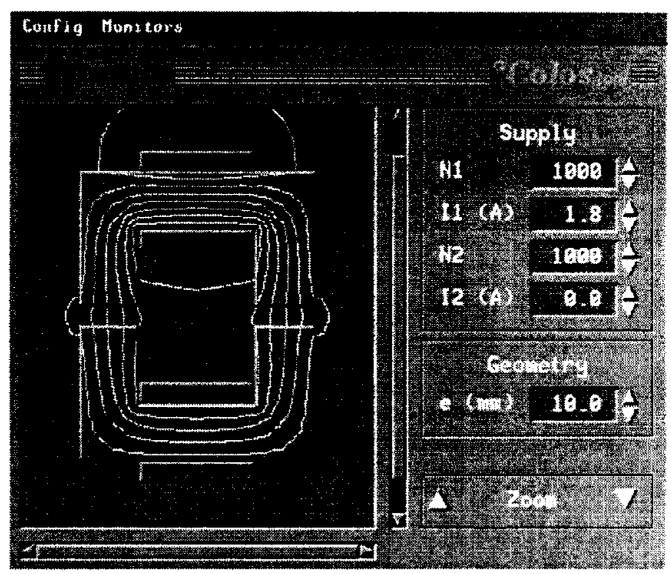

Fig. 2. *Contact* user interface: main window

As results (Fig. 3), the students visualize the amplitude of the flux density, represented with color shading. They may also superimpose field lines. *Contact* gives them also access to a real time updated table of results, showing the field value at a few characteristic points, the flux through the airgap surface, and other meaningful quantities such as energy or force.

With this type of application, we are looking for the students to understand the magnetostatic phenomena, including the influence of the saturation, get the range values of these phenomena, and understand some physical concepts, such as the Ampere law [3].

III. The Finite Element Model

The main goal of computer aided education is to offer the students a highly interactive environment allowing them to examine any desired configuration of the studied device with instant feedback. Taking into account the non-linearity of the materials made unavoidable the use of the F.E.M.

The F.E.M. by itself is well known for such an analysis and does not lead to any problem [4]. We worked mainly at the implementation of the F.E.M., which has been optimized as much as possible in order to minimize the solving times and to get a real time feedback.

One can mention:

- the discretization is performed using first order triangles
- the problem is described with one symmetry
- the structure of the mesh does not vary: only the vertical coordinates of the nodes may change, because of the possible modification of the airgap
- the structure of the F.E. matrix is then prestored
- all the local sub-matrices are precomputed, except the ones corresponding to the airgap
- the nested dissection renumbering algorithm [5] is used to solve the system matrix
- in non-linear cases, the solution corresponding to the previous state of the magnetic circuit is taken as initial solution, decreasing then the number of iterations.

The mesh (Fig. 4) is made of 468 triangles and 270 nodes. On a mid-range workstation with a 75 Mips computation power (HP9000/712), a linear solution takes about 30ms to be computed, and a non-linear solving goes up to 600 ms: this is compatible with the maximum delay required by a smooth animation.

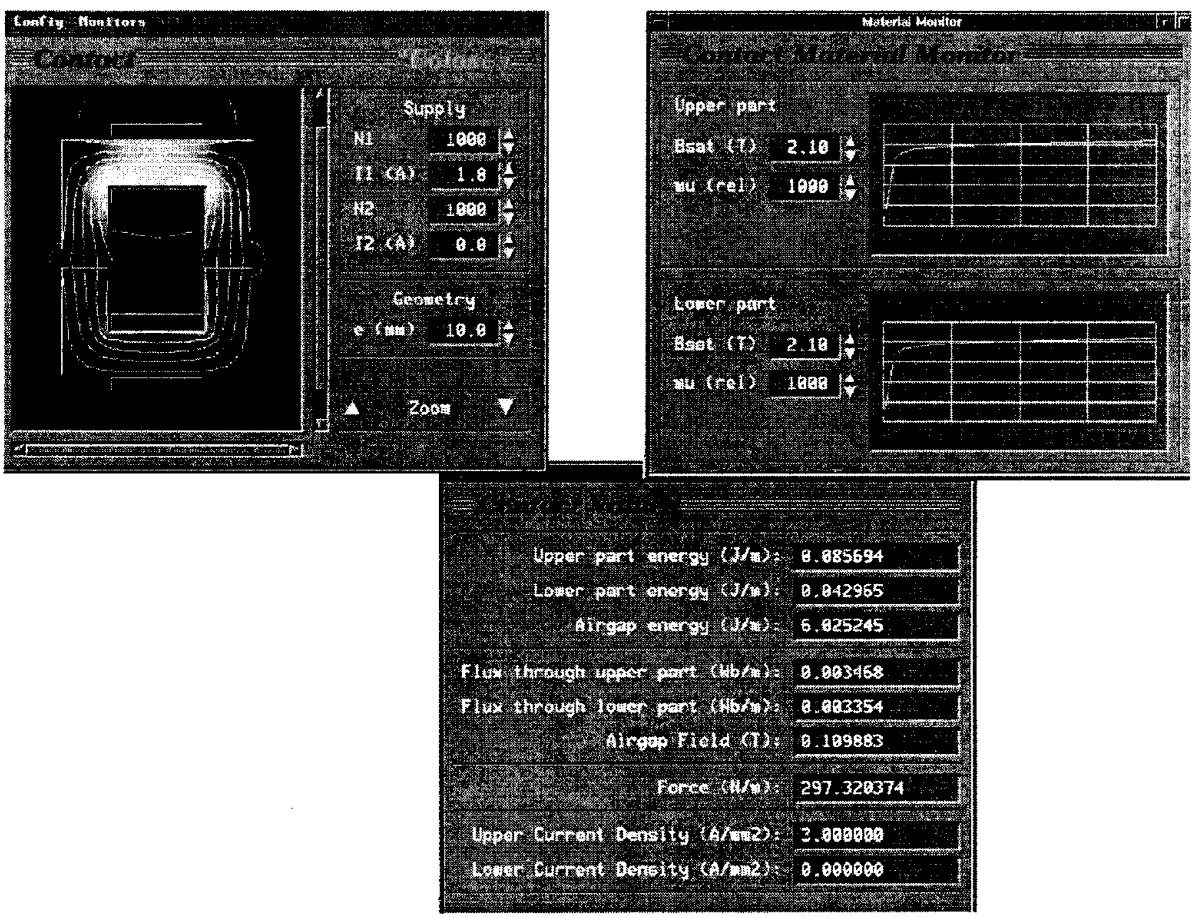

Fig. 3: *Contact* complete user interface: main window, window for the monitoring of the magnetic materials, and table of results.

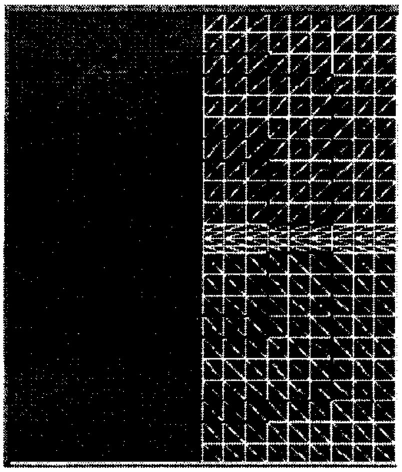

Fig. 4. Mesh used for the F.E. Computation.

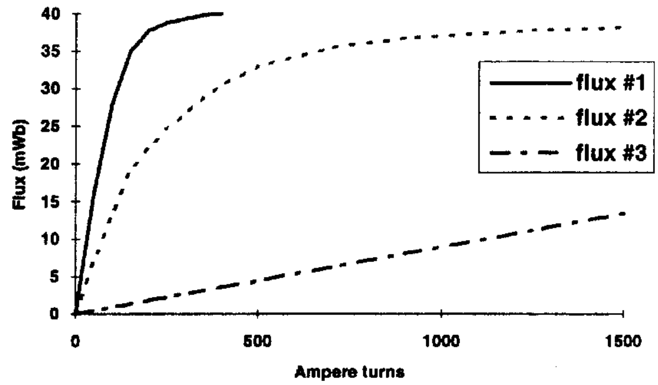

Fig. 5 Example of relation deduced by the students. Flux vs current, for different values of airgap and permeability. #1: airgap=0.1 mm, μr=10000. #2: airgap=0.1 mm, μr=1000. #3: airgap=4 mm, μr=1000.

IV. GUIDELINES FOR THE PRACTICAL WORK.

A guide is provided to the students to perform the practical work. First, this guide proposes them to examine qualitatively several aspects of electromagnetism:

- the influence of the permeability on the distribution and on the value of induction lines when currents are constant, magnetic materials non saturated and without airgap.
- the influence of the width of the airgap on the induction value at a given current. This influence is studied for small and large values of magnetic material permeability.
- the evolution of the magnetic state of the circuit when the sum of the ampere-turns remains constant, but distributed in different manners (remind that the number of turns and intensity of both coils can vary independently).
- the influence of the saturation of one arm of the circuit on the flux. The parameter settings are chosen in order to strongly saturate one material, the other parameters can vary.

Quantitative aspects are also approached. For different values of the airgap and permeabilities, students have to evaluate:

- the distribution of magnetic energy between the air (airgap) and the magnetic materials.
- the relationship between the flux and the current (Fig. 5).
- the variation of the force in relation with the flux.

V. EVALUATION

In order to test the pedagogical efficiency of this new approach, we have made an evaluation of the students through a multiple choice questionary (M.C.Q.). Note that the notions used during the practical work have been previously exposed during a classical lesson. Therefore students should be able to reply correctly to all questions. We have asked students to perform this M.C.Q. at the beginning and at the end of the session.

A. The Multiple Choice Questionary

Questions concern theoretical aspects of magnetostatics and aspects linked to orders of magnitudes that appear in the practice. The M.C.Q. is composed by the ten next affirmations:

#1: in a magnetic circuit with a large airgap, the magnetic energy is essentially located in the iron.

#2: the Ampere's law is only true for linear materials.

#3: a high permeability magnetic circuit canalizes the lines of the B-field.

#4: with given designing data, the magnetic field only depends on the sum of the ampere-turns.

#5: with a large airgap the flux does not depend on the value of the relative permeability (if it is higher than 1000).

#6: the relation flux vs current is non linear if materials present a saturation of the B(H) curve.

#7: a large airgap makes difficult the saturation of a magnetic circuit.

#8: the attraction force between two parts of a magnetic circuit is proportional to B^2.

#9: when one of the arms of the magnetic circuit is saturated, the flux does not vary mainly in function of the other parameters (current, permeability,...).

#10: with no airgap and small current, the induction field is proportional to the relative permeability.

The students have to tell if each of these affirmations are true, false or if they ignore the answer. The scores are established by counting +1 for a correct answer, -1 for a false answer, or 0 if no answer. Hence the score can range between -10 and +10.

B. Analysis of the results

Answers concern a population of 221 students, which is significant on a statistical point of view. These results can first be analysed globally. Fig. 6 shows the distribution of students versus the score that they have obtained at the beginning and at the end of the session. 199 students progress while 11 have stable results and 11 regress. At the end of the session there is a 4 points increase of the mean value of the scores. Indeed this mean value rises from 2.9 to 6.9. The population scoring 5 or more increases from 56 to 187 individuals. 40 students obtain the maximal score at the end while only one gets it at the beginning. Undoubtedly the work performed by the students using this package improves strongly their level of knowledge.

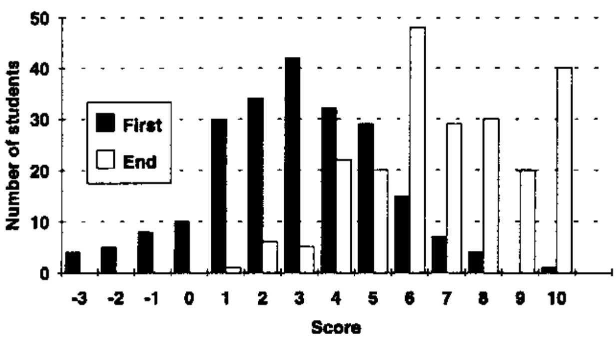

Fig. 6. Evolution of the score of the students between the beginning and the end of the practical work.

The evolution of scores may also be analysed on the basis of each question. It allows to test the pertinence of the questions. Fig. 7 shows the rate of good answers (number of good answers divided by the total number of answers):

- at the beginning of the session the average rate is about 45% with a large dispersion depending on the questions: for example, the question #2 has a success rate close to 75% while the question 5 does not exceed 16%.

- at the end of the session, about 80% of students answer correctly. This rate fluctuates only a little with the questions: from 72% for the question #8 to 99% for the question #3.

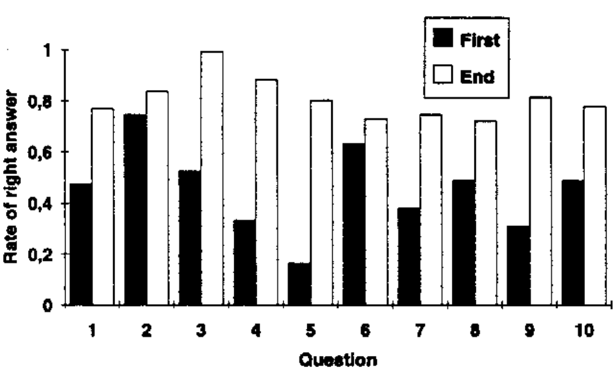

Fig. 7. Rate of good answers for each question.

Fig. 8 shows the efficiency of the work session. It is calculated as the number of students who switch from a false or "don't know" answer to a correct answer, divided by the number of false answers at the beginning of the work. Questions #2 and #6 show a low efficiency because they have a good initial success rate. This is not surprising: the notions approached in these questions are simply deduced from classical laws of electromagnetism, and students are supposed to know them since a long time. On an other hand, question #5 shows a good efficiency, which is also not surprising: it deals with a quantitative aspect of electromagnetism, which is less known by students.

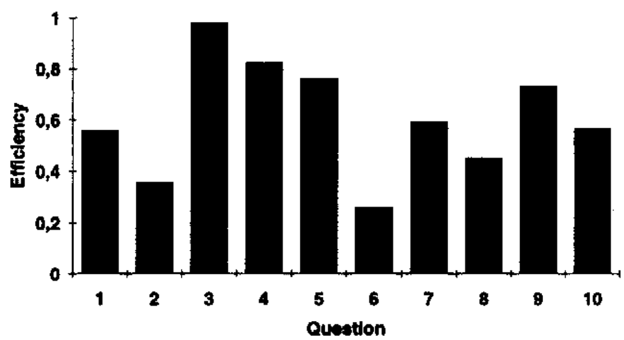

Fig. 8. Efficiency of the work session.

CONCLUSION

We have described in this paper a C.A.E. package for non-linear magnetostatics. This package is based on the F.E.M. which has been greatly optimized in order to obtain fast computation times. From a pedagogical point of view, it seems to be really efficient when used in parallel with a classical lecture. Same M.C.Q. will be used next year to evaluate how the knowledge of the students is improved. The students will also be tested a few weeks after the practical work, in order to know how durable is their learning.

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