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CHALLENGES IN FEM APPLICATION IN SELECTED DOMAINS OF ELECTRICAL ENGINEERING

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Abstract: In the last three decades Finite Element Method / Analysis (FEM / FEA) has gained well-deserved acceptance as a modelling tool in macro-scale, static- and low/medium/high-frequency electromagnetics. It allows better engineering designs, providing insight into complex interactions between field vectors and the ferromagnetic or paramagnetic solids. Despite steady progress, there are still issues which have got no general numerical solution, and tend to be tackled using various simplifications. Two such modelling challenges are presented in detail, namely the eddy current induction in a 3D moving conductor, and the accurate, yet practical representation of material hysteresis loop. Brief software preview is carried out, and some experiences from Author's commercial R&D projects are described.

keywords: Finite Element Method, ferromagnetic hysteresis, motion induction

1. INTRODUCTION

In technical electromagnetics, a strong motivation exists for development of numerical methods. In majority of cases, there is no other accurate means of getting insight into magnetic/electric fields inside or even at the surface of a bulk ferromagnetic object.

Among numerical methods, FEM / FEA analyses of electromagnetic phenomena proved useful in broad range of industries, the energy and transportation sector taking the lead. Brief but useful background on electromagnetic simulations can be found in [1] and [2]. Monograph [3] is more exhaustive and detailed, but requires more theoretical knowledge to be understood. The publications on mechanical finite element method can be helpful as well, because the structural FEM and electromagnetic FEM share many common notions, including spatial discretisation, shape functions, boundary conditions, and decomposition of arbitrary phenomenon into systems of linearised equations. On the other hand, the particularity of underlying physical formulas – Maxwell laws - make any electromagnetic analysis significantly different from any structural one.

Practical application of FEM requires well-informed choice of computer software. An engineer or a scientist, interested in electromagnetic FEM cab choose between commercial programs, public free-ware codes and in-house tools not made available to anyone but their developers. From the point of view of applications, electromagnetic FEM software can be roughly divided in three categories:

- varied static and low-frequency=LF (2D, 3D magneto-statics / dynamics, electrostatics, induction heating, circuit coupling); low-to-medium frequencies range from 0.1 Hz up to kHz-range, with majority of applications at 50 Hz
- high-frequency, often abbreviated as HF (telecommunication, EMC=Electromagnetic Compatibility, microwave heating)
- advanced physics (simulation of particles, laser, plasma, fusion, waves-matter interaction)

In the second and the third group the Finite Element Method plays in auxiliary role, while in the domain of statics and low-to-medium frequency applications it is the key algorithm.

Another distinction can be made between multi-purpose software with pre- and post-processing GUI (e.g. ANSYS MAXWELL, OPERA, COMSOL, FLUX3D), and alternatively those algorithms which work in text-mode only ("black-box" or open source solvers). The latter are usually academic free-ware libraries, like DEAL-II. [4]. There are as well free-ware programs equipped with some GUI, e.g. EMAP [5], RillFEM [6], or FEMM [7], the latter being able to solve 2D planar and axisymmetric problems in low frequency magnetics, electrostatics, and heat flow as an auxiliary feature.

Some companies deliver their products as a series of separate, specialised moduli, e.g.

- MAGNUM, AETHER, XENOS (Field Precision company)
- MAGNET, ELECNET, MOTORSOLVE (Infolytica)

Yet another group of tools is devoted to circuit simulations (SPICE, SABER, EMTP, PSIM).

A useful list of products can be found in [8]. Such a list should, however, be treated with caution and regularly updated, because the simulation software evolves and the programmes are often rebranded.

2. ALGORITHM DEVELOPMENTS

2.1. Magnetic hysteresis loop (MHL)

The magnetic hysteresis phenomenon influences to various extent the distribution of magnetic fields, energy losses and waveforms of electric parameters such as torques and induced

voltages. The practical occurrences of this phenomena are transformers, actuators, motors, generators, brakes, medical and scientific devices.
In ferromagnetic materials with significant hysteresis, the relationship between the magnetic induction (B) and intensity (H) is ambiguous. This means, that a given local state (B,H) depends on the previous magnetic history and is a function of time. Fig. 1 presents a measured qualitative major hysteresis loop obtained from a duplex steel bulk sample.

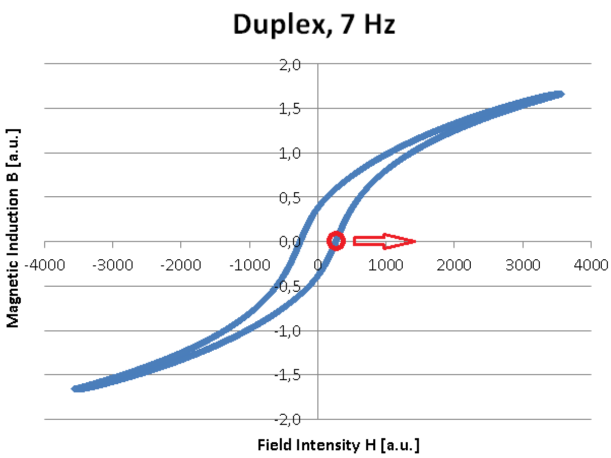

Fig.1. Experimental measurement of hysteresis loop in a 150x20x6 mm duplex steel sample

Apart from major loops, minor loops can be formed, if the range of variation of H is reduced. The arrow shows the influence of the magnetising frequency, which tends to cause an apparent increase of the coercive field (H_c). The effect is due both to the intrinsic material hysteresis and the activity of eddy currents, and has practical consequences for the performance of almost any electrical machines, therefore needs to be taken into account in numerical analysis.

An idealised set of rules governing the shape of magnetic hysteresis loops was proposed over 100 years ago by Mandelung. He postulated a unique dependency of loop's shape on starting and ending H, along with "return-point-memory" and "wiping-out property". Reproducing these conditions is the first, basic yet demanding test for hysteresis models. In [9] Dupré gives a comprehensive review of these models along with their advantages and limitations, including:
- Preisach family of algorithms [10], described briefly further on
- Empirical PDEs, including Jiles-Atherton-Sablik approach [11]
- PDEs derived directly from fundamental thermodynamics [12]
- Geometric methods [13]
- Neuron network systems [14]

The Preisach model and its numerous extensions is popular and versatile. It refers to the magnetic microstructure of the material by employing statistical description of so-called dipoles. Such dipoles adopt an "on" value (+1.0) when the external H exceeds a certain threshold α, and an "off" (-1.0) value below β. Their behaviour depends additionally on the history or recent reversals, i.e. the instants in which the variation of H changed from increasing to decreasing or the opposite. Classical Preisach model defines the instantaneous irreversible magnetisation value as a sum of so-called Preisach dipoles:

$$M_{irr} = \int_{-\infty}^{\infty} d\alpha \int_{-\infty}^{\alpha} d\beta \;\; P(\alpha,\beta)\,\phi(\alpha,\beta,H,H_{hist})$$

where: α - "up-switching" field, β - "down-switching" field,
Φ - a function of field intensity H and its variation history H_{hist} adopting only +1 or -1 values.
The classical Preisach model is rate-independent and scalar. Vector extensions cover possible rotation of the magnetisation vector. Altogether they are flexible yet enabling physical interpretation of parameters. Moreover, another popular group of models based on "macroscopic" constitutive equations (Hodgon, Jiles-Atherton-Sablik) turned out to be derivable from Preisach approach.

2.2 Moving conductor induction (MCI)

DC or AC magnetic field leakage is relatively simple to simulate, as long as all the components are fixed. Dynamic (moving conductor) Field Leakage – is much more difficult to handle properly. It is especially true for NDT systems commonly termed as P.I.G.s (Pipeline Inspection Gauges), where an inverse problem is to be solved. Such a NDT set-up aims at deducing the shape and dimensions of a flaw, out of the voltage induced in a pick-up coil moving relatively fast along the pipeline. Modeling MCI is relevant as well in any electrical machine with rotating parts.

There seem to be two computation approaches, both encountering numerical difficulties as the relative movement velocity increases. The first approach is quasti-static, i.e. the simulation resembles the magnetostatic problem. In a practical case, De Gersem [15] considers a DC magnetic brake with an uniform solid cylinder rotating at high speeds. In-house, non-public software is applied in a quasi-static regime with a "transport term". Both the iron core and the field generating stator component have got a saturable, though anhysteretic B(H) curve. Thank to the uniformity of the rotor, time stepping and moving mesh, typical of the transient approach, can be avoided. The same problem as observed by the Author is encountered, namely the field amplitude distributions get meaningless at high speeds, corresponding to the Péclet's number above 1.0. The difficulty is overcame with a simultaneous application of so-called upwinding algorithm and mesh adaptivity.

Another approach consists in representing the movement in several time-steps, applying some type of electromagnetic coupling between the objects in relative movement. For example, Gay [16] resigns from the quasi-static method applied by De Gersem [15], and opts for a full transient solution, because it does not require uniformity of the conductor along the movement vector. The permanent magnets are represented by material with a constant non-zero coercivity (identical to the workaround described by the Author in paragraph 3.1). The rotating disc is saturable, and its meshing (3D hexahedra) is refined at the surface in order to model accurately the skin depth effect. Notably, Gay fails to obtain convergence when relative magnetic permeability of the discs exceeds 400. This is consistent with Author's experience: high permeability, entering far into saturated B(H) region, and fast changes of the excitation field entail serious difficulties to obtain convergent solutions in the time-transient regime [17].

2.3. Software implementation of MHL and MCI

As far as the magnetic hysteresis modelling is concerned, it usually requires either a huge computational effort, and/or material data difficult to acquire. However, relatively efficient algorithms requiring minimum amount of experimental data have been emerging recently. [18,19], cf Table 1. For example, OPERA relies on the "trajectory" method, whose path is determined by interpolation from the actual measured magnetic induction and applied field characteristics of the major loop. The turning points of the trajectory are used to predict the behaviour of arbitrary minor hysteresis loops. This produces results of acceptable accuracy without extensive computation, and without the need to acquire atypical material properties.

The motion effects seem to have more implementations than MHL in the leading FEM software. For example, FLUX3D software was applied to solve a full-transient motion induction problem [16]. OPERA is distinct for the possibility of modelling MCI an MHL simultaneously. According to user's manuals, all the programmes listed in Table 1 are capable of reproducing MCI either in a quasi-static or transient FEM simulation.

Table 1. Capability of leading FEM software to solve hysteresis loop / motion induction problems

	Hysteresis loop	Motion effects
ANSYS Emag: MHL / MCI	-	Quasi-static (uniformity requirement)
ANSYS Emag: Extra Functions	1D circuits, power loss macros, electromagnetic contact; tracing charged particles	
ANSYS (Ansoft) Maxwell 3D: MHL / MCI	Vector model, for soft and hard magnetic materials (only limiting single B(H) major loop required)	Transient
ANSYS (Ansoft) Maxwell 3D: Extra Functions	Template for electric machines	
COMSOL Multiphysics: MHL / MCI	- not directly, External Matlab algorithm (Fixed-Point Technique) coupled with Comsol [20]	Quasi-static (uniformity not required in 2D! [see MAXWELL_CRACK) Transient: not directly External Matlab algorithm coupled with Comsol [21]
COMSOL Multiphysics: Extra Functions	Direct definition of PDEs Beyond the typical scope of FEA simulations.	
MagSoft Flux3D: MHL / MCI	- not in general FEA module, but available in electric machine tool SPEED	Quasi-static or transient (remeshing, electromagnetic contact)
MagSoft Flux3D: Extra Functions	Strong support for thermal phenomena	
Cobham (ex Vector Fields) OPERA: MHL / MCI	Transient scalar, "trajectory" model (only limiting single B(H) major loop required); some silicon steel data included [18]	Transient; CARMEN/LM and CARMEN/RM modules Can be modeled simultaneously with hysteretic material properties!
Cobham OPERA: Extra Functions	Module for electric machines: Opera Electrical Machines Environment; Charged Particles Devices; Radio-Frequency and Microwave simulations	

3. OWN EXPERIENCES: FUNDAMENTAL RESEARCH AND COMMERCIAL PROJECTS

The Author has had the opportunity to work on almost all the domains of electromagnetics, including magnetostatics, DC current conduction, electrodynamics, low-frequency (Hz-range) magnetodynamics, and wave propagation. Two areas turned out to be particularly challenging for numerical implementation. First was the distribution of fields and eddy current vectors in case of relative movement of the exciting field and the conductor. Second demanding task involved a fit-for-purpose representation of magnetic hysteresis.

In the electromagnetic practical problems described below, ANSYS Multiphysics tool was systematically applied. However, the encountered difficulties are universal and can be faced regardless of the software used.

3.1. Magnetic hysteresis loop

In three research studies the hysteretic behaviour of the ferromagnetic sample was considered an important factor. These studies concerned respectively:

- MFM microscopy calibration (micromagnetics)
- Critical reassessment of so-called Metal Magnetic Memory NDT (magnetistatics)
- Insight into C-core magnetised bulk ferromagnet (Low-Frequency magnetodynamics)

ANSYS has no hysteretic (B,H) functionality available, although the B(H) relationship can be nonlinear and exhibit saturation. To account for magnetic hysteresis, a workaround was found, by attributing a certain coercivity value [A/m] to the material. This parameter, along with a definition of magnetic permeability, shifts the B(H) curve away from (0,0), thus producing at least a portion of the hysteresis loop.

The approach worked best in case of Metal Magnetic Memory study, an interesting qualitative methodology having significant quantitative limitations [22]. The constant non-zero coercivity of order of 200 A/m represented well the initial (remanent) magnetisation of the sample, which was then placed at different angles relative to the weak, ambient magnetic field.

The constant coercivity technique proved partially successful in the most complex among studied problems, namely modelling of the MFM (Magnetic Field Microscopy) probe in the vicinity of the polished ferromagnetic sample. The study aimed at computing the forces acting on the probe's tip in the non-uniform magnetic induction in close vicinity (1-10 μm) from the material's surface. Far-fetched assumptions had to be made as to the geometry of magnetic domains, each featuring a certain magnetisation vector and anisotropic relative permeability. The simplified approach did not allow representation of de-magnetisation, i.e. movement of domain walls or rotation of magnetisation vectors.

In C-core magnet NDT analysis, the intrinsic (static) material magnetic hysteresis was eventually considered negligible as related to the eddy-current (dynamic) hysteresis.

In all the described cases, the workaround with constant coercivity only allowed representation of small variations of magnetic induction around a fixed (B,H) work point. As the full major hysteresis loop could not be traced, the method did not allow e.g. a simulation of magnetic storage devices.

3.2. Micromagnetic phenomena used in NDT

In development of electromagnetic NDT methods, the knowledge on precise space/time variation of magnetic induction within the material is essential to optimise the methodology. Particular attention has been paid to the Magnetic Barkhausen Noise (HBN) and Magnetoacoustic Emission (MAE), because these signals carried useful information about stress state of the studied component. Electromagnetic FEM was applied in a EC-funded project MAGSTRESS, aiming at extension of existing non-destructive and semi-nondestructive methods to anisotropic steels. The simulation reproduced successfully important characteristics of the magnetic induction both within the sample and in the surrounding air. The computed stray field correlated well with the experiment. Next step consisted in reproducing subtle, secondary effects, such as HBN and EMA. Impossible as it was with direct FEM, requiring descent to microscale in terms of both time and space, some empirical formulas derived from experiment proved useful to simulate HBN and EMA waveforms.

Picture 2 represents the dual-core magnetising set-up placed upon a 10 mm thick plate. The mesh is regular and refined at the centre, where the magnetic response is to be calculated and measured.

Picture 3 shows the computed variation of the magnetic induction at six different depths of the plate. The phase shifts between the plots are due to the activity of eddy currents, which retard the flux and prevent it from effectively penetrating the inside of the material.

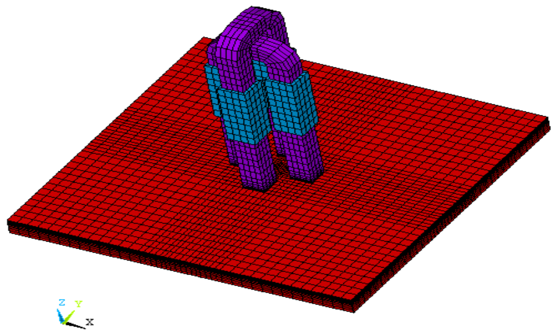

Fig. 2. Discretisation of a double-core magnetic NDT set-up for transient nonlinear FE calculations

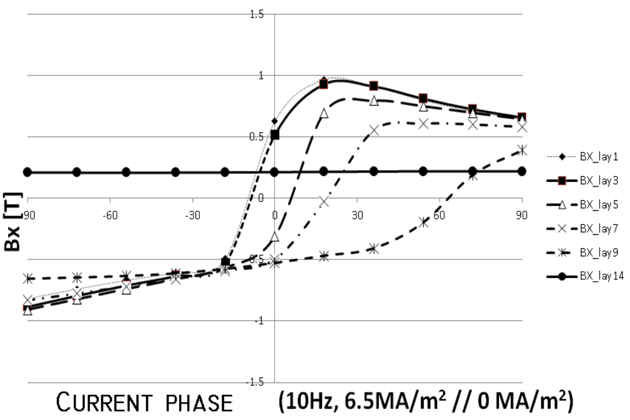

Fig. 3. Magnetic induction within a ferromagnetic sample related to the phase of the magnetising current (90 deg. corresponds to the current's maximum)

3.3. Harmonic excitation of eddy currents within a moving conductor

A research project consisted in reproducing 3D signals at detector coils while train wheels were passing. The flux lines adopted two distinct paths, one coming around the wheel ("air path"), and another, involving penetration of the metal to the depth of about S_d ("skin path"). The skin depth was found to be approximately equal to 1/100 mm.

In order to model the behaviour of the field penetrating the skin depth accurately, one would thus need around 100 million elements in a 1m x 1m x 1m model, which remained prohibitive in the context of industrially useful research. Even if such a large model was created and computed, correct results would not be guaranteed, because of several other factors of uncertainty, such as model's extent, boundary conditions and details of electrical circuit.

Ultimately a relatively coarse mesh was created, and only the signal's amplitude was studied. The calculated amplitude changes were corroborated experimentally. The phase shift, as expected, did not correlate with the experiment. It was due to the different sensitivity of amplitude B_{amp} and phase θ_B (Eq. 3, Eq. 4) to the Real and Imaginary components of the field intensity at the detection coils.

$$B^2_{amp} = Re(B)^2 + Im(B)^2 \qquad (2)$$

$$\theta_B = atan\,(Im(B)/Re(B)) \qquad (3)$$

The imaginary component related to the "skin path" of the flux lines, and was prone to large uncertainty due to rough meshing. As the Real component was about 10 times larger than the Imagiinary one, the aforementioned uncertainty did not influence much the amplitude, but it still had detrimental effect on the calculated phase shift.

In the research, a 2D approach turned out to be irrelevant, because it produced results both quantitatively and qualitatively wrong. The 3D approach brought better results, predicting well the changes of signal's amplitude between the new wheels and some worn-out ones. As the frequency of excitation (range of kHz) was much higher than the angular frequency of the wheels, the motional induction effects could be neglected without further loss of accuracy.

3.3. Electromagnetic brakes

The research project consisted in evaluating the efficiency of high-speed train brake prototype. ANSYS allowed for quasi-static velocity-induced effects, provided the moving conductor's section normal to the movement direction did not vary in time. This was a particular challenge for the project, because the rotating circular part had complicated structure with ribs and venting holes. Two work-arounds were proposed. First approach reduced the prototype to a 2D representative section. This gave a reasonable assessment of the order of amplitude of Lorentz forces, but starting from a certain rotational speed, the results turned out to be highly dependent on mesh density (compare with similar observations in [15] and [16]).

Another attempt was made to replace movement effects with a harmonic variation of excitation currents, at a frequency equal to the frequency of rotation of the aluminium disc. This, however, did not reproduce the intrinsic phenomenon of asymmetric field "lag" behind the moving object.

Finally, no more than a first approximation of brake's torque could be found with FEM. This could probably be assessed with similar accuracy using hand formulas, such as the one from [15].

3.4. Transformer insulation break-down

The task consisted in assessment of risk of electrical break-down between the low-voltage (700 V) and high-voltage (10 kV) windings of a large industrial transformer working at 50 Hz. The specification required that there was no break-down if 1 mm-large metal inclusions penetrated into the insulating layer between the windings. The problem was well suited for application of FEM because of the geometric dimensions that could be optimised. On the other hand, the literature on the "avalanche" effect [23, 24] reveals phenomena which are definitely non-macroscopic and non-deterministic, so they did

not fit the standard FEM schemes. An arbitrary threshold of 10^6 N/C of electric field magnitude was adopted, and a few different inclusion shapes were modelled. It was assumed, that the appearance of field peak above the threshold indicated the break-down substantial risk. Certainly, the field magnitude increased with the sharpness of particle's edges, and the spherical inclusion was the least harmless as opposed to the needle-shaped ones. The true answer to the "pass/fail" question asked by the transformer's producer required thus an assessment of failure probability.
It is interesting to note, that a correct representation of the insulating medium (lubrified paper or air) required the electrical conductivity close, but not exactly equal to zero. Otherwise the electrical potential distribution between the coils were qualitatively wrong without any warning issued by the program.

3.5. High-current shielding

In high-power electrical devices (transformers, generators, motors), a need for efficient shielding often arises. One research project aimed at validation of a shield preventing excessive AC-induced magnetic field from penetrating the encompassed space. Tightly wrapped induction coils were used. The external (unwanted) sinusoidal magnetic field induced an opposing flux on the grounds of Faraday's law and Lenz law. The set-up was globally well suited for FEM, but a serious problem consisted in the representation of the structure of the induction coils. One, direct solution involved painstaking modelling of every strand, which would roughly require 10^7 – 10^8 elements. Otherwise it would be beneficial to apply some super-element representing accurately the properties of an induction coil. Such an element would have to produce a circumferential emf and induced current density, constant along the coil's axis, and satisfying conservation of current. Unfortunately, such a formulation was not available in ANSYS, even though a super-element existed for representation of an excitation coil, and the reverse phenomenon could easily be accounted for. Finally, only a rough approximation of real shielding device could be obtained with FEM.

3.6. Summary table

The table below summarises the difficulties encountered in the selected Authors' projects.

Table 2. Challenges in R&D simulation projects

	1	2	3	4	5
SHIELDING	X	X		X	
BARKHAUSEN	X		X	X	X
kHZ-DETECTOR	X	X		X	
TRANSFORMER	X	X	X		
MICROWAVE	X		X		X

Legend:
1: accuracy is an issue; 2: mili-macro scale; 3: software limits, non-standard physics; 4: exceptional resources required; 5. unusual material data required

Although almost all the electromagnetic tasks tackled by the Author could not be solved quantitatively (lack of precise material data, software and hardware limitations), FEM was successful at reproducing qualitative characteristics of the fields and indicated the direction of beneficial prototype modifications. It was possible to obtain meaningful relative-quantitative results, i.e. "the signal will increase by 20% if a given dimensions decreases by 10%". In some analyses a statistical approach was recommended, but still deterministic FEM could provide the basis for DOE and sensitivity analysis. The recent software developments might allow some progress, but fundamental limitations indicated in the table 2 shall probably remain difficult to overcome in applied electromagnetic simulations.
Although almost all the electromagnetic tasks tackled by the Author could not be solved quantitatively (lack of precise material data, software and hardware limitations), FEM was successful at reproducing qualitative characteristics of the fields and indicated the direction of beneficial prototype modifications. It was possible to obtain meaningful relative-quantitative results, i.e. "the signal will increase by 20% if a given dimensions decreases by 10%". In some analyses a statistical approach was recommended, but still deterministic FEM could provide the basis for DOE and sensitivity analysis. The recent software developments might allow some progress, but fundamental limitations indicated in the table 2 shall probably remain difficult to overcome in applied electromagnetic simulations.

4. CONCLUSIONS: LASTING CHALLENGES

As electromagnetic field problems tend to be less intuitive than mechanical tasks, the electromagnetic FEM tends to be more complicated and more prone to produce unnoticed errors. Along with the increasing availability and easiness of use of the computational software, risks of misuse become more and more significant.

There is a wide range of non-standard, nonlinear effects which can have a sine-qua-none importance for realistic FEM simulation. These include ferromagnetic material hysteresis, high-frequency skin effect, motion induction, permanent magnets with temperature-dependent properties etc.

There is a variety of element formulations for even basic applications, as magnetostatics (MVP, MSP, Edge-Flux). Moreover the 2D and 3D element formulations may differ considerably, which can well illustrated by differences between PLANE82 and SOLID117 / SOLID236 elements in ANSYS.

Some final practical points to follow when planning an electromagnetic FEA are listed below:

- seemingly similar projects may significantly vary in degree of difficulty, due to the inclusion or non-inclusion of the non-standard, non-linear effects
- Careful judgement is requires to decide, which of the mentioned effects can safely be neglected or not
- There is always a trade-off between accuracy and cost; obtaining an arbitrary level of accuracy often becomes infeasible for fundamental numerical reasons or because of software limitations
- There is no fit-for-all-purposes electromagnetic FEM software, neither commercial nor public; the latter group of tools usually lacks extensive pre-processing tools, and should be avoided in context other than fundamental academic research.

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WYZWANIA W STOSOWANIU METODY ELEMENTOW SKOŃCZONYCH W WYBRANYCH ZAGADNIENIACH ELEKTROTECHNICZNYCH

Słowa kluczowe: Metoda Elementów Skończonych, Histereza Magnetyczna, Efekty Indukcyjne

W przeciągu ostatnich trzech dekad metoda elementów skończonych (MES) została stopniowo uznana jako narzędzie użyteczne w modelowaniu makroskopowych elektromagnetycznych zagadnień statycznych, jak również nisko-, średnio- i wysoko-częstotliwościowych. Pozwala projektować bardziej wydajne urządzenia, dając wgląd w złożone interakcje pomiędzy parametrami wektorowymi pola magnetycznego i elektrycznego a ciałem stałym. Pomimo nieustających postępów, wciąż istnieją zagadnienia nie posiadające w pełni zadowalającego ujęcia numerycznego, i są rozwiązywane z pomocą daleko idących uproszczeń. W artykule szczególna uwaga poświęcona jest zjawiskom indukcyjnym w przewodnikach znajdujących się we wzajemnym ruchu, a także sposobom odwzorowania pętli histerezy ferromagnetycznej. Dodatkowo dokonany jest krótki przegląd programów obliczeniowych opartych na MES oraz podsumowane są doświadczenia z wybranych projektów badawczo-rozwojowych Autora.