How Accurate is Computer Simulation of Induction Systems?

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Criteria of nearness
Factors influencing accuracy
- Considered processes
- Geometry (incompleteness, variation during processing, simplification, etc.)
- Material properties (electromagnetic, structural, thermal, mechanical)
- Formulation of electromagnetic task
- Simulation methods and algorithms
  - Examples of simulation
  - Summary
What is Accuracy?

• Accuracy is the nearness of calculated and “true” values.
• Common definition associates accuracy with systematic errors and precision with random errors.
• For each particular case and model, simulation is precise in sense of repeatability of the results but not always accurate.
• Experiments are not precise and not quite accurate but they are the most reliable “in large” providing a general picture of the situation and taking into account all the complex of phenomenae and environmental conditions.
• Evaluation of errors is extremely important for optimization of calculation process, optimal design and control. Big contribution in this field was made by experts from St. Petersburg, Hannover, Samara, Padua and other scientific schools.
Simple Case of Accuracy Analysis

\[ Z_i = \text{Re}Z + j \text{Im}Z \]

“Concentrated” parameters (impedances, efficiency, power, currents, voltages, etc.) are very important for simulation of the whole induction system including power supplies and matching circuits.

“Distributed” parameters (power density, fields, temperatures, stresses, hardness pattern, etc.) are necessary for evaluation of quality of the process. Different criteria of nearness may be applied for evaluation of accuracy.
Example: Temperature Distribution during Transverse Heating of Strip

Is this field “near” to a required one? Is it optimal? Is it correctly calculated?

Nikanorov, A., Schulbe, H., Galunin, S.: From expert solution to optimal design of electrothermal installations, J. Elektrowarme Int., Heft 4, 2004
First publications on Numerical Simulation of Induction Systems

Temperature distribution in the ingot radius, 1D FDM EM+T computer simulation, Holmsdahl and Sundberg, ASEA, 1963

2D EM computer simulation of induction systems by Inductively Coupled Circuits method, E. Kolbe and W. Reiss, 1963

This was the simplest method of integral equations.

FEM (FEA) was used for simulation of induction systems approximately 10 years later.

Because of low speed and memory of hardware, many simplifications were required resulting in inaccuracy of simulation.
Evolution of “Hardware”

Logarithmic ruler, before 1965...
.... and later

Mechanical calculator, before 1970s

Programmable electronic calculator Casio, 1970s and later
Evolution of Hardware

Big Electronic Machines 1965 – 1990s; limited access for induction system simulation

Modern personal computer, since 2000

Powerful computers and huge improvement in software allow us to solve multiphysic problems. Sources of simulation inaccuracy are shifted to the problem formulation, properties of materials and other user-related issues.
Computer Revolution in Induction Heating Technology

Old approach, old people: huge practical experience, low trust in computer simulation

New approach, new people: low practical experience, absolute trust in computer simulation

Best practice: *synergy of practical experience, theory and simulation!*
Factors that Influence Accuracy of Simulation

Problem Description and Solution are mutually dependent; effectiveness and accuracy of simulation depends on proper choice at each stage.
Scheme of Processes in Induction Heat Treating

- Process Control
- Machine Operating Mode
- Power Supply Circuits
- Thermal Process (Heating)
- Electromagnetic Process
- Cooling / Quenching
- Stresses
- Distortions
- Structural Transformations
- Final Product

New!
System Description

• Majority of practical simulations are being made now in 1D or 2D approaches
• Structure and geometry of real induction systems are often very simplified
• In reality a majority of induction systems are 3D
• Interference of induction device and source of power must be considered in many cases
• One of the problems – frequency variation during the process.
3D Effects in Cylindrical Coils

Is this coil 2D?

Multi-turn internal coil looks like axisymmetrical but must be considered as 3D due to 3 components of magnetic field
3D Effects in Multi-turn Cylindrical Coils

Using copper wedges (equalizers) in attempt to make the coil field 2D
3D Effects in Multi-turn Cylindrical Coils

“Dog Leg” connection of plane-parallel turns can result in big distance between leads
Almost 2D Multi-turn Coil

Busbars

\[ t_2 = t_1 \cos \alpha; \text{ for } \alpha = 45^0 \quad t_2 = 0.707t_1 \]
“Ground” Current

Effect of “ground” current is often observed in systems with multi-turn coils for heat treating and forging, as well as HF welding.

Special connection of coils is often used for elimination of ground current but it reduces efficiency and power factor.

_No publications on simulation of ground currents are familiar to the author._

Usually these currents are detrimental, causing damage of contact bodies, roll bearing, etc. However they may be used for benefits....
Trico Beam Hardening Using “Ground” Current

Temperature distribution

- Hair-pin coil

- Split-n-Return coil

Split-n-Return coil with a reactor in the external circuit
Material Properties

Properties for simulation of electromagnetic and thermal problems:

- Density $d(T)$
- Specific heat $c(T)$
- Electrical resistivity $\rho(T)$
- Magnetic permeability $\mu(H, T)$.

Main problems are with specific heat and especially with magnetic permeability.

Problems with specific heat:
- Data availability for different structures of materials
- Approximation of data in zones of structural transformation
- No account for chemical reaction (e.g. oxidation in forge heating)
- A set of calculations showed that an error in temperature can reach 10%. 
Specific Heat of Steel 1040

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<th>Temperature</th>
<th>Specific Heat (J/(g·°C))</th>
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<tr>
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Source: database of program Elta 6.0
On The Specific Heat of Carbon Steels

by Saburo’ Umino

The science reports of the Tohoku University,
Sendai university, 1926

Pure Iron, 0% C

Nearly pearlitic steel, 0.8% C
Magnetic Permeability \( \mu \) of Steels

\( \mu \) is sensitive to material composition, structure, field strength and temperature. In many cases it is anisotropic.

**Main questions:**

1. How to characterize \( \mu \) at alternating fields?
   
   Time domain approach was published by M. Kogan in 1966.
   
   However more simple approach based on ideas of L. Neiman (1940s) and Slukhotsky (1950s) were commonly used. It uses a certain “equivalent” value of \( \mu \) during the whole period of field.

   Our knowledge about accuracy of this approach in induction heating conditions is insufficient. Only recently some attempts were made for simulation of EM field in Time Domain in induction heating.

2. Calculation of hysteresis losses. Majority of programs neglect them compared to eddy-currents. It becomes quite incorrect in heating of particulated materials.

3. Some programs consider \( \mu \) constant in depth. It is well known that this assumption reduces absorbed power up to 30%.

4. Behavior of magnetic materials at temperatures close to Curie point.
No.1 Time-Domain Solution of 1D EM Problem

Waveforms of H and B in magnetic cylinder for sinusoidal external field strength, Time Domain simulation by M. Kogan, 1966
No.3 Striation Effect

M. Divilkovsky, $f = 477$ kHz (left) and 242 kHz (right). Armco iron

Striation or Zebra Effect

Zebra effect should not be mistaken for a "Barber's pole" effect, well known in induction. Barber’s pole effect demonstrate helical stripes, caused by slow part rotation/feed ratio in scanning processes.
Surface Temperature Distribution vs. Time

Temperature Dependence of Mu and Simulation of Zebra Effect

Dependence of permeability vs. temperature for a carbon steel for different field intensities; marks show permeability value calculated with a formula below

\[ \mu(T) = 1 + (\mu - 1)(1 - \left(\frac{T}{T_k}\right)^n) \]

Temperature distribution on the surface of a part heated in a long single-turn inductor. \( n = 16 \)

Approximation of \( \mu = f(T) \)

Source: program Elta 6.0
Summary

• Computer simulation is a great tool for research, development, learning and teaching
• It can be very accurate when the task is correctly formulated and proper simulation technique selected
• The user of simulation must be a good expert in induction technique; it is vital
• Modern computer allows us to solve difficult problems of induction heating; the cutting edge is “non-linear coupled 3D EM+Thermal+XXX” problems
• There are many programs for simulation of induction heating but their ability and limitations (causing inaccuracies) are not well investigated and described
• Material characterization and databases are the key problems in achievement of high accuracy
• International collaboration is required for further advancement of simulation technique.
THANK YOU FOR ATTENTION!

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