

Table of Contents

| | |
|---|------|
| Introduction | xiii |
| Javad FOULADGAR | |
| Chapter 1. Thermal and Electromagnetic Coupling | 1 |
| Javad FOULADGAR, Didier TRICHET and Brahim RAMDANE | |
| 1.1. Introduction | 1 |
| 1.2. Electromagnetic problem | 2 |
| 1.2.1. Local formulation of the electromagnetic problem | 2 |
| 1.2.1.1. Maxwell's equations | 2 |
| 1.2.1.2. Interaction between electromagnetic waves and materials | 3 |
| 1.2.1.3. Vector and scalar potentials | 4 |
| 1.2.2. Boundary conditions | 5 |
| 1.2.2.1. Boundary conditions between two different media | 5 |
| 1.2.2.2. Boundary conditions at the domain's limits | 6 |
| 1.2.3. Functional spaces | 6 |
| 1.2.4. Tonti diagrams | 7 |
| 1.2.5. Different formulations of the electromagnetic field | 8 |
| 1.2.5.1. Magnetostatic formulation | 8 |
| 1.2.5.2. Magnetostatic formulation in magnetic vector potentials | 10 |
| 1.2.5.3. Magnetodynamic formulation | 10 |
| 1.2.5.4. Magnetodynamic formulation in A-V | 11 |
| 1.2.5.5. Magnetodynamic formulation in T-T ₀ - ϕ | 11 |
| 1.2.5.6. Formulation in H- ϕ [DUL 96] | 12 |
| 1.2.5.7. Uniqueness conditions | 12 |
| 1.2.6. Time harmonic form | 13 |
| 1.2.6.1. Maxwell's equations in the time harmonic form | 13 |

| | |
|--|-----------|
| 1.2.6.2. Electromagnetic power | 13 |
| 1.3. Thermal problem | 15 |
| 1.4. Magnetothermal coupling | 16 |
| 1.5. Solving the electromagnetic and thermal equations | 18 |
| 1.5.1. Analytic methods | 18 |
| 1.5.1.1. Transient state | 18 |
| 1.5.1.2. Harmonic state | 18 |
| 1.5.2. Semi-analytic methods. | 20 |
| 1.5.2.1. Shell elements and surface impedance methods | 20 |
| 1.5.2.2. Generalized shell element formulation of a conductive plate | 21 |
| 1.5.2.3. Moment method | 23 |
| 1.5.3. Numerical models | 27 |
| 1.5.3.1. Finite volume method without velocity terms | 28 |
| 1.5.3.2. Finite volume method with a velocity term | 30 |
| 1.5.3.3. Finite element method | 31 |
| 1.6. Conclusion | 35 |
| 1.7. Bibliography | 36 |
| | |
| Chapter 2. Simplified Model of a Radiofrequency Inductive Thermal Plasma Installation | 39 |
| Javad FOULADGAR and Jean-Pierre PLOTEAU | |
| 2.1. Introduction. | 39 |
| 2.2. Plasma and its characteristics | 40 |
| 2.2.1. Plasmas | 40 |
| 2.2.2. Properties of thermal plasma | 41 |
| 2.2.3. Inductive thermal plasma | 41 |
| 2.2.4. Thermal inductive plasma installation. | 43 |
| 2.2.5. Inductive thermal plasma start-up and maintenance | 44 |
| 2.2.5.1. Plasma start-up | 45 |
| 2.2.5.2. Plasma maintenance | 47 |
| 2.3. Modeling a plasma installation | 49 |
| 2.3.1. Torch simulation | 50 |
| 2.3.1.1. Simplification | 50 |
| 2.3.1.2. Solving the electromagnetic equation | 51 |
| 2.3.1.3. Solving the heat equation | 53 |
| 2.4. Calculating charge impedance. | 57 |
| 2.4.1. Results | 57 |
| 2.4.2. Local validations | 60 |
| 2.4.2.1. Magnetic field measurement method | 60 |
| 2.4.2.2. Temperature measurement method | 60 |
| 2.4.2.3. Results | 62 |

| | |
|--|-----------|
| 2.5. Generator model | 64 |
| 2.5.1. Triode generator | 64 |
| 2.5.2. Modeling the HF generator in the steady state | 64 |
| 2.5.2.1. Principle of the developed model | 65 |
| 2.5.2.2. Triode modeling | 67 |
| 2.5.2.3. Quasi-analytic generator simulation | 69 |
| 2.5.2.4. Results | 73 |
| 2.5.3. Complete simulation of a thermal plasma installation | 75 |
| 2.5.3.1. Coupling algorithm | 75 |
| 2.5.3.2. Validation of the complete installation simulation model | 76 |
| 2.5.3.3. Calculating the installation's efficiency | 78 |
| 2.6. Conclusion | 80 |
| 2.7. Bibliography | 81 |
| | |
| Chapter 3. Design Methodology of A Very Low-Frequency Plasma Transformer | 85 |
| Javad FOULADGAR and Sourì Mohamed MIMOUNE | |
| 3.1. Introduction | 85 |
| 3.2. Different types of very low-frequency applicators | 87 |
| 3.2.1. Choice criterion of very low-frequency plasma applicators | 88 |
| 3.3. Simplified analytical model for analysis and preliminary design | 88 |
| 3.3.1. Hypotheses | 89 |
| 3.3.2. System equation | 90 |
| 3.3.3. Plasma maintenance criterion | 93 |
| 3.3.4. Flaws of the linear model | 95 |
| 3.4. Nonlinear model | 97 |
| 3.4.1. Nonlinear model results | 98 |
| 3.5. Plasma stability in the transitory and sinusoidal states | 100 |
| 3.5.1. Transitory state | 100 |
| 3.5.2. Sinusoidal state | 101 |
| 3.6. Advanced inductive plasma transformer model | 103 |
| 3.6.1. Displacement current | 103 |
| 3.6.2. Electromagnetic equation formulation | 104 |
| 3.6.2.1. Introducing a voltage source | 105 |
| 3.6.3. Thermal equation formulation | 107 |
| 3.6.4. Coupling algorithm for the electromagnetic and thermal equations | 107 |
| 3.6.5. Results of the 3D model | 109 |
| 3.6.6. Impact of the number of arms of the magnetic core on the electric field distribution | 110 |
| 3.7. Plasma initialization | 111 |
| 3.7.1. Initialization with a capacitive discharge | 112 |

| | |
|---|------------|
| 3.7.2. Initialization with an inductive discharge | 112 |
| 3.7.3. Towards an inductive ignitor | 113 |
| 3.8. Conclusion | 114 |
| 3.9. Bibliography | 114 |
| Chapter 4. Non Destructive Testing by Thermo-Inductive Method | 117 |
| Javad FOULADGAR, Brahim RAMDANE, Didier TRICHET and Tayeb SAIDI | |
| 4.1. Introduction. | 117 |
| 4.2. Principles of the thermo-inductive method | 119 |
| 4.2.1. Installation schematic | 119 |
| 4.2.2. Describing the technique's elements | 121 |
| 4.2.2.1. Induction generator. | 121 |
| 4.2.2.2. The inductor | 122 |
| 4.2.2.3. The infrared camera | 122 |
| 4.2.2.4. The specimen to inspect | 123 |
| 4.2.3. The stimulation modes. | 123 |
| 4.2.3.1. Modulated stimulation mode | 123 |
| 4.2.3.2. Pulse stimulation mode | 124 |
| 4.2.3.3. Pulse phase mode. | 125 |
| 4.3. Basic thermo-inductive technique theory | 126 |
| 4.3.1. One-dimensional models for the propagation of the thermal wave in a continuous medium | 126 |
| 4.3.1.1. Propagation of thermal waves in a semi-infinite medium excited by a constant flux. | 127 |
| 4.3.1.2. Propagation of thermal waves in a semi-infinite plate with a horizontal flaw | 132 |
| 4.3.2. One-dimensional model limitations | 138 |
| 4.3.3. Numerical models | 141 |
| 4.3.3.1. Electromagnetic models | 141 |
| 4.3.4. Magneto-thermal coupling | 144 |
| 4.3.5. Applying numerical model to study the feasibility of the thermo-inductive technique | 144 |
| 4.4. Application of the thermo-inductive method to inspect massive magnetic steel components | 145 |
| 4.4.1. Studied setup | 145 |
| 4.4.2. Flaw's influence on the distribution of the induced currents and temperature | 147 |
| 4.4.3. Study of the inductor's influence. | 150 |
| 4.4.3.1. Shape and position of the inductor. | 150 |
| 4.4.3.2. Air gap between the inductor and the inspected component. | 150 |

| | |
|---|------------|
| 4.4.4. Choice of induction generator | 152 |
| 4.4.5. Acquisition parameters | 152 |
| 4.4.6. Influence of the heating time and the electromagnetic frequency | 154 |
| 4.4.6.1. Heating time | 154 |
| 4.4.6.2. Electromagnetic frequency | 156 |
| 4.4.7. Influence of the flaw's geometry | 157 |
| 4.4.7.1. Influence of the flaw depth/flaw length ratio. | 157 |
| 4.4.7.2. Flaw orientation. | 159 |
| 4.4.8. Experimental results | 162 |
| 4.5. Comparison with infrared thermography | 164 |
| 4.5.1. Studied setup | 164 |
| 4.6. Applications on composite materials | 168 |
| 4.6.1. Study of composite materials | 168 |
| 4.6.1.1. Studied setup | 169 |
| 4.6.1.2. Study of the inductor's influence. | 170 |
| 4.6.1.3. Influence of the electromagnetic frequency and heating time | 170 |
| 4.6.1.4. Influence of the flaw depth | 173 |
| 4.6.1.5. Influence of flaw thickness | 175 |
| 4.6.1.6. Influence of the delamination width. | 176 |
| 4.6.2. Experimental study | 177 |
| 4.6.2.1. Inspection of the drilled plate. | 178 |
| 4.6.2.2. Inspection of the plate with a hole opening on a surface | 182 |
| 4.7. Conclusion and general instructions | 185 |
| 4.7.1. Discussion on the choice of induction generator and inductor | 185 |
| 4.7.2. Discussion on data acquisition | 188 |
| 4.7.3. Flaw characterization. | 189 |
| 4.7.3.1. Surface flaws | 189 |
| 4.7.3.2. Deep flaws | 189 |
| 4.7.3.3. Delaminations. | 190 |
| 4.8. Bibliography | 190 |
| Chapter 5. Induction Heating of Composite Materials | 195 |
| Javad FOULADGAR, Didier TRICHET, Samir BENSALD and Guillaume WASSÉLYNCK | |
| 5.1. Introduction. | 195 |
| 5.2. Composite materials. | 197 |
| 5.2.1. Composite material definition | 197 |
| 5.2.2. Composite material constituents | 197 |

| | |
|---|-----|
| 5.2.2.1. The matrix | 198 |
| 5.2.2.2. The reinforce | 198 |
| 5.2.3. Composite architecture | 200 |
| 5.3. Lifecycle of composite materials | 202 |
| 5.4. Induction and the lifecycle of composite materials | 203 |
| 5.4.1. Mastery of induction heating of composite materials | 203 |
| 5.4.1.1. Simulation tool | 203 |
| 5.4.1.2. Adapting the inductor's form and frequency to the geometry, the material, and the type of heating | 204 |
| 5.4.1.3. Precise knowledge of the physical properties | 206 |
| 5.5. Identifying the physical properties of composite materials by experimental methods | 207 |
| 5.5.1. Influence of the geometry | 207 |
| 5.5.2. Induced current methods | 209 |
| 5.5.2.1. Measuring the electrical conductivity of a conductive plate | 210 |
| 5.5.2.2. Analytic impedance calculation | 211 |
| 5.5.2.3. 2D numerical method | 214 |
| 5.5.3. Sensitivity analysis | 217 |
| 5.5.4. Impedance measurements | 219 |
| 5.5.4.1. Optimization of the measurement system | 219 |
| 5.5.4.2. Experimentation and results | 222 |
| 5.6. Homogenization techniques | 224 |
| 5.6.1. Inverse problem | 225 |
| 5.6.1.1. Application of the inverse problem to stratified composite materials | 226 |
| 5.6.1.2. Thermal characteristics | 228 |
| 5.6.2. Dynamic homogenization methods for periodic structures | 231 |
| 5.6.2.1. Homogenization of the electrical conductivity | 232 |
| 5.6.2.2. Thermal properties | 234 |
| 5.6.2.3. Applications to the 2D electromagnetic study of composite materials | 235 |
| 5.6.2.4. Applications to the 2D thermal study of composite materials | 241 |
| 5.6.2.5. Applications to 3D materials | 241 |
| 5.6.3. Homogenization by the representative samples method | 243 |
| 5.6.3.1. The method's principle | 244 |
| 5.6.3.2. Generating the geometry | 246 |
| 5.6.3.3. Results | 248 |
| 5.6.3.4. Influence of contacts between differently oriented folds | 249 |
| 5.7. Heating composite materials by induction | 251 |

| | |
|---|------------|
| 5.7.1. Studied setup | 251 |
| 5.7.2. Inductor. | 251 |
| 5.7.3. The composite plates. | 252 |
| 5.7.4. Experimental validation setup | 253 |
| 5.8. Setup model | 253 |
| 5.8.1. Electromagnetic formulation | 254 |
| 5.8.2. Thermal formulation | 255 |
| 5.9. Influence of the folds' orientation. | 260 |
| 5.10. Difficulty of the electrothermal coupling | 262 |
| 5.10.1. Study of the sensitivity of the induced power's variation as a function of the temperature | 262 |
| 5.11. Validating the electrothermal model | 262 |
| 5.11.1. 13-fold composite | 263 |
| 5.11.2. 16-fold composite | 265 |
| 5.12. Conclusion | 267 |
| 5.13. Bibliography | 268 |
| List of Authors | 273 |
| Index | 275 |