TIME TABLE

TIME	Monday June 3	Tuesday June 4	Wednesday June 5	Thursday June 6	Friday June 7
9.00 - 9.45	Registration	Klinkel	Daniel	Krejčí	Pechstein
09.45 - 10.30	Krejčí	Klinkel	Daniel	Krejčí	Kaltenbacher
11.00 - 11.45	Krejčí	Klinkel	Kaltenbacher	Klinkel	Kaltenbacher
11.45 - 12.30	Krejčí	Klinkel	Kaltenbacher	Pechstein	Belahcen
14.00 - 14.45	Pechstein	Daniel	Belahcen	Pechstein	
14.45 - 15.30	Pechstein	Daniel	Belahcen	Kaltenbacher	
16.00 - 16.45	Pechstein	Daniel	Belahcen	Kaltenbacher	
16.45 - 17.30	Poster Session I	Poster Session II	Belahcen	Belahcen	
18.00	Welcome aperitif				

ADMISSION AND ACCOMMODATION

The course is offered in a hybrid format, allowing participants the flexibility to attend either in person or remotely via the Microsoft Teams platform. Limited spots are available for on-site attendance and will be allocated on a first-come, first-served basis.

Registration fees:

- On-site participation: 600.00 Euro + VAT*
Includes a complimentary bag, five fixed menu buffet lunches, hot beverages, downloadable lecture notes.
Deadline for on-site application is May 3, 2024.

- Live Streaming Online Participation: 250.00 Euro + VAT*
Includes downloadable lecture notes.
Deadline for online application is May 22, 2024.

Application forms should be submitted online through the website:
http://www.cism.it.
A confirmation message will be sent to accepted participants.

Upon request, a limited number of on-site participants can be accommodated at CISM Guest House at the price of 35 Euro per person/night (contact: foresteria@cism.it).

 * where applicable (bank charges are not included) - Italian VAT is 22%.

CANCELLATION POLICY

Applicants may cancel their registration and receive a full refund by notifying the CISM Secretariat in writing (via email) no later than:
- May 3, 2024 for on-site participants (no refunds after the deadline);
- May 22, 2024 for online participants (no refunds after the deadline).
Cancellation requests received before these deadlines will be subject to a 50.00 Euro handling fee. Incorrect payments are also subject to a 50.00 Euro handling fee.

GRANTS

A limited number of participants from universities and research centres who do not receive support from their own institutions can request a waiver of the registration fee and/or free lodging.
Requests should be sent to the CISM Secretariat by **April 3, 2024**, along with the applicant's curriculum vitae and a letter of recommendation from the head of the department or a supervisor confirming that the institute cannot provide funding. Preference will be given to applicants from countries that sponsor CISM.

For further information please contact:
CISM (Seat of the course)
Palazzo del Torso - Piazza Garibaldi 18 - 33100 Udine (Italy)
tel. +39 0432 248511 (6 lines)
e-mail: cism@cism.it | www.cism.it

HYSTERESIS IN FUNCTIONAL MATERIALS: FROM PHYSICAL MODELS TO NUMERICAL SIMULATION

Advanced School coordinated by

Manfred Kaltenbacher
TU Graz, Austria

Astrid Pechstein
Johannes Kepler University Linz, Austria

Udine *June 3 - 7* 2024

HYSTERESIS IN FUNCTIONAL MATERIALS: FROM PHYSICAL MODELS TO NUMERICAL SIMULATION

The hysteretic behavior of certain materials provides the basis for the design of many of today's "smart" systems. Prominent example are ferroelectric and ferromagnetic materials, which have been adopted as sensors and actuators in diverse fields of applications, ranging from microelectromechanical systems (MEMS) for high-precision positioning to vibrational and structural noise control as well as hearing aids. As these materials are taken to their limits by increasing incident fields, frequencies, decreasing size, reaction times as well as transition to large deformation applications, a detailed knowledge on the underlying physics is necessary to enable accurate multi-physics simulations.

The response of ferroelectric or ferromagnetic materials depends on their state of remanent polarization or magnetization and the presence of external electric or magnetic fields. In classical appli-cations, the remanent polarization or magnetization state is assumed as uni-directional and constant. As the operational range of sensors and actuators is extended, this assumption is no longer valid, and an accurate understanding of the evolution of the material's internal state is imperative. Hysteretic effects observed in multiferroic materials are usually modelled by means of internal variables. The internal variables can be, e.g., remanent magnetization or polar-ization, internal strains or phase fractions, and can describe the microstructure at the macroscopic level of the material.

The main aim is to provide a comprehensive course teaching the fundamentals of hysteretic material behaviour. The course's content includes the physics of ferroelectrics and ferromagnetics, phenomenological material mod-els, thermodynamically consistent hysteresis models and their mathematical analysis, efficient numerical simulation schemes, and measurement set-ups for deriving the model parameters of real materials.

The course will start with an overview of scalar and vector hysteresis models followed by a detailed discussion of variational inequalities as the principal math-ematical tool in hysteresis model-ling, hysteresis energy balance, and continuous data dependence. Classical elasto-plasticity serves as an exemplary use-case, where thermodynamic potentials and dis-sipation functions are defined and their relation to commonly used yield conditions and associated flow rules is shown. The concepts developed there provide the basis for modeling ferroelectric material behavior appearing in piezoelec-tric ceramics. Next, the transition from microscopic to macroscopic level will be discussed for ferro-magnetic materials, addressing also the origin of domain struc-tures, domain wall motion and the rotation of magnetization. At this point, the identification of the material parameters based on measurements will be explained. Hysteresis modeling in materials undergoing large deformations, such as polarizable or magnetiz-able electro-active polymers, will conclude the theoretical part of the course. For all the above ap-plications, theoretical models are complemented by efficient finite element strategies. In a practical session at the end, participants are encouraged to experiment on the behaviour of different hyster-esis models in simple computa-tional setups, which will support the understanding of the theories presented throughout the week.

The course will also include two poster sessions, in which the par-ticipants are invited to introduce themselves and to present their current research topics.

PRELIMINARY SUGGESTED READINGS

Eringen, A.C. und Maugin, G.A. (1990). Electrodynamics of Con-tinua I: Foundations and Solid Media. Springer.

Maugin, G.A. (1988). Continuum mechanics of electromagnetic solids. In J.D. Achenbach, B. Budiansky, W.T. Koiter, H.A. Lau-werier, and L. Van Wijngaarden, Hrsg., Applied Mathematics and Mechanics, 33. North-Holland Series.

Krejčí, P. (1996). Hysteresis, Convexity and Dissipation in Hy-perbolic Equations, volume 8 of GAKUTO Internat. Ser. Math. Sci. Appl. Gakkotosho Co., Ltd., Tokyo.

Belahcen, A. (2005). Magne-toelastic coupling in rotating electrical machines. IEEE Trans-actions on Magnetics, 41(5), 1624-1627.

Klinkel, S. (2006). A phenomeno-logical constitutive model for ferro-lastic and ferroelectric hysteresis effects in ferroelectric ceramics. International Journal of Solids and Structures, 43(22-23), 7197-7222.

Belahcen, A. (2006). Vibrations of rotating electrical machines due to magnetomechanical cou-pling and magnetostriction. IEEE Transactions on Magnetics, 42(4), 971-974.

Daniel, L., Rekik, M., & Hubert, O. (2014). A multiscale model for magneto-elastic behaviour including hysteresis effects. Ar-chive of Applied Mechanics, 84, 1307-1323.

Humer, A., Pechstein, A. S., Meindl-humer, M., & Krommer, M. (2020).

Nonlinear electromechanical coupling in ferroelectric materials: large deformation and hysteresis. Acta Mechanica, 231, 2521-2544.

Nierla, M., Kaltenbacher, M., & Rupitsch, S. J. (2022). Computa-tion of rotational hysteresis losses by vector Preisach models based on rotational operators. COM-PEL-The international journal for computation and mathematics in electrical and electronic engineer-ing, 41(3), 981-995.

LECTURES

All lectures will be given in English. Lecture notes can be downloaded from the CISM web site. Instructions will be sent to accepted participants.

INVITED LECTURERS

Anouar Belahcen - Aalto University, Finland
5 lectures on: material models used in the FE simulations of electrical machines, including linear models, nonlinear single-valued models, and hysteresis models both scalar and vectorial; electromagnetic force computation in electric machines and nodal magnetic forces for high order elements; a practical course on the implementation of the nodal force computation method within a FE solver.

Laurent Daniel - CNRS, CentraleSupélec, Université Paris-Saclay, Sorbonne Université, France
5 lectures on: a discussion of the origin of ferromagnetic behaviour from the microscopic mechanisms (origin of domain structure, domain wall motion, magnetisation rotation) to the macroscopic ferromagnetic behaviour and hysteresis; introduction of a multiscale approach for the modelling of magneto-elastic couplings using the Jiles-Atherton model.

Manfred Kaltenbacher - TU Graz, Austria
5 lectures on: a detailed discussion of the energy based hysteresis model used in electromagnetics, which is based on the dry friction model as used in mechanics, its variational formulation and its solution via optimization; identification of the hysteresis parameters based on measurements; an advanced FE formulation and its implementation in an open source software.

Sven Klinkel - RWTH Aachen, German
5 lectures on: the non-linear analysis of piezoelectric structures including material non-linearities appearing in ferroelectric ceramics; development of a fully thermodynamic consistent model; implementation in a finite element framework and discussion of consistent tangent moduli; implementation of shell finite elements including a summary and explanation of additional electro-mechanical locking effects.

Pavel Krejčí- Czech Technical University, Prague, Czech Republic
5 lectures on: a survey of mathematical models for scalar and vectorial hysteresis models with applications in elastoplasticity, ferromagnetism, porous media, phase transitions, and multifunctional materials; variational inequalities as the principal mathematical tool in hysteresis modeling, hysteresis energy balance, and continuous data dependence, and the solvability of systems of (partial) differential equations.

Astrid Pechstein - Johannes Kepler University Linz, Austria
6 lectures on: an introduction into classical elastoplasticity as a first example of material models involving hysteresis with a detailed discussion of the involved internal variables, thermodynamic potentials and dissipation function; modeling of ferroelectric materials in large deformation context; efficient numerical treatment by appropriate finite element methods; a practical session on the implementation of these thermodynamically consistent models.