Universität Stuttgart

Second International Workshop

Direct and Inverse Problems in Piezoelectricity

Hirschegg (Kleinwalsertal), Austria, July 16-19, 2006

W. Geis, A.-M. Sändig (eds.)

Berichte aus dem Institut für Angewandte Analysis und Numerische Simulation

Programmheft 2006/006

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Institut für Angewandte Analysis und Numerische Simulation (IANS)
Fakultät Mathematik und Physik
Fachbereich Mathematik
Pfaffenwaldring 57
D-70 569 Stuttgart

E-Mail: ians-preprints@mathematik.uni-stuttgart.de
WWW: http://preprints.ians.uni-stuttgart.de

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Second International Workshop

Direct and Inverse Problems in Piezoelectricity

Hirschegg (Kleinwalsertal), Austria, July 16-19, 2006

Organisers: W.Geis, A.-M. Sändig (Stuttgart)

Piezoelectric devices used as actuators or sensors are of growing interest in different applications. There are still open basic problems in theory, numerical simulation, material science and manufacturing processes. The objective of the workshop is, to bring together researchers from different disciplines as mechanics, mathematics, material science and industrial partners. Lectures and discussions on several aspects of piezoelectricity will inform on the state of the art and fructify both research and practical application.

The topics cover:

- Inverse problems, such as: design and structure optimisation, parameter identification and corresponding numerical methods.
- Theoretical problems, such as: constitutive properties, hysteresis, polarisation.
- Discussion of temperature influence, eigenfrequencies, damage and cracks and corresponding numerical simulations.
- Applications, industrial challenges, manufacturing.

This second workshop on piezoelectricity will continue and extend the first Workshop at the RICAM [1] in Linz in October 2005.

This workshop is supported by the DFG (Deutsche Forschungsgemeinschaft) in the framework of the project 436 GEO 122/1/06.

Winfried Geis, Anna-Margarete Sändig

Stuttgart, June 2006

[1] http://www.ricam.oeaw.ac.at/sscm/srs_ev/kaltenbacher/

Programme

Monday, July 17

8:00	**Breakfast**
9:00	**Opening**
9:05–9:50	**M. Kamlah** Poling of piezoceramic tubes
9:50–10:30	**M. Nicolai** Poling technologies of piezoceramics under electromechanical and thermal conditions
10:30–10:50	**Coffee break**
10:50–11:35	**B. Kaltenbacher** Preisach operators and hysteresis modelling in piezoelectricity
11:35–12:10	**A. Konstandin** Finite element computation of the constitutive behavior of PZT at electromechanical loading
12:10–14:00	**Lunch**
14:00–14:45	**M. Krommer** Structural control of frame structures by piezoelectric actuation and sensing: theory and experimental verification
14:45–15:30	**J. Becker** Flatness–Based Feedforward Control Design for Flexible Piezoelectric Structures
15:30-16:00	**Coffee break**
16:00–16:45	**A. Hauck** Simulation of Thin Piezoelectric Structures Using Higher Order Finite Elements
16:45–17:30	**P. Steinhorst** Mixed FEM for piezoelectric problems - recent work and difficulties
18:30	**Dinner**

Tuesday, July 18

8:00	**Breakfast**
9:00–9:45	**D. Natroshvili** Interaction Problems of Metallic and Piezoelectric Materials with Regard to Thermal Stresses
9:45–10:30	**T. Michelitsch** Elektroelastische Greensche Funktion des transversal-isotropen (hexagonalen) unendlichen Mediums
10:30–10:50	**Coffee break**
10:50–11:35	**O. Chkadua** The Solvability and Asymptotics of Solutions of Crack-Type Boundary Value Problems of Thermopiezoelectricity
11:35–12:20	**M. Scherzer** About the development of strength criteria of piezoelectric interface corner configurations
12:30–14:00	**Lunch**
14:00–18:00	**Walking Tour**
18:30	**Dinner**

Wednesday, July 19

8:00	**Breakfast**
9:00–9:45	**T. Lahmer** Homogenization Techniques in Sensor/Actuator Applications
9:45–10:00	**Coffee break**
10:00–11:15	**W. Geis/A.-M. Sändig** Asymptotic models for piezoelectric stack actuators with thin metal inclusions
11:15	**Closing**
11:30	**Lunch**

Abstracts

Flatness–Based Feedforward Control Design for Flexible Piezoelectric Structures

Jens Becker and Lothar Gaul
Universität Stuttgart, Institut für Angewandte und Experimentelle Mechanik (IAM)
Email: `becker@iam.uni-stuttgart.de`

This contribution presents a solution to the feedforward tracking control problem for flexible beam structures exemplified for a beam with piezoelectric actuation. The design methodology is based on the modal analysis of the structural dynamics to determine an inverse system representation by parameterizing modal states and system input in terms of a parameterizing function and its time-derivatives. In addition, the analytical feedforward control design approach is adapted to incorporate the finite–element method, which makes this approach especially suitable for the control of structures with complex geometry, spatially varying material properties or distributed control inputs, e.g. as encountered in piezoelectricity. Simulation results for a clamped–free Timoshenko beam under feedforward control with piezoelectric actuation are presented. Hereby it is desired to drive the beam tip from zero deflection to a given desired stationary deflection within a finite–time interval. Experiments show good agreement with the simulations and prove the applicability of the control design. The feedforward control is also very beneficial to closed–loop structural control scenarios if an additional vibration feedback control is used to control residual vibrations due to unknown nonlinearities, model errors or external disturbances. Again, this application scenario is investigated in both simulations and experiments.

Three-dimensional finite element modelling of a piezoelectric actuator with regard to thermal effects

Tengiz Buchukuri, David Natroshvili and OtariChkadua
A. Razmadze Mathematical Institute, Georgian Academie of Sciences
Email: t_buchukuri@yahoo.com

We consider a piezo-ceramic slab with embedded relatively thin metallic plates (electrodes). In the "metallic" part of the structure a four dimensional thermoelastic field is described by the displacement vector and the temperature, whereas in the the piezo-ceramic domain we have a five dimensional physical field described by the displacement vector, temperature and the electric potential.

We give the weak formulation of the mixed boundary transmission problem of pseudo-oscillation equations describing the interaction of metallic and piezoelectric materials with regard to thermal effects and show coercivity of the related sesquilinear form. By variational methods then we prove existence and uniqueness of the week solution to the problem in question.

The finite element modelling and analysis of the problem is built upon cubic volume elements. We derive a finite element system of equations regarded to the problem and prove its unique solvability. We establish convergence of the method as the volume of the elements tends to zero. A numerical example demonstrating the influence of thermal effects is presented.

The Solvability and Asymptotics of Solutions of Crack-Type Boundary Value Problems of Thermopiezoelectricity

Otari Chkadua, Tengiz Buchukuri and David Natroshvili
A. Razmadze Mathematical Institute, Georgian Academie of Sciences
Email: chkadua@rmi.acnet.ge

The paper deals with the solvability and asymptotics of solutions of three-dimensional boundary value problems of thermopiezoelasticity for homogeneous anisotropic bodies with cracks. We assume that on the crack faces either the Neumann boundary conditions or the mixed boundary conditions (the Dirichlet condition on one crack face and the Neumann condition on the other one) are given.
The existence and uniqueness theorems for solutions of the boundary value problems are obtained by using the potential theory and the general theory of pseudodifferential equations on manifolds with boundary.
Employing an asymptotic expansion of solutions of strongly elliptic pseudodifferential equations and an asymptotic expansion of potential-type functions, for sufficiently smooth data of the problem we have obtained a complete asymptotic expansion of solutions near the crack edges. It is proved that the exponent of the first leading term in the asymptotic expansion of solutions to the problem with the Neumann boundary conditions near the crack edge is equal to $1/2$.
We establish the asymptotic behaviour of solutions to the mixed problem near the crack edge. In particular, we have found a class of anisotropic piezoelectric bodies (comprising, for example, $Te\,O_2$) for which the oscillation of solutions vanishes near the crack edge. In this case the first three leading terms of the asymptotics do not contain logarithms and singularity of solutions can be calculated by a simple formula. These exponents depend on the material constants as well as on the geometry of the crack edge. They may take on any value from the interval $(0; 1/4)$. For some classes of piezoelectric media the singularity of solutions to the mixed problem near the crack edge can reach the value $1/4$. For example, piezoelectric medium with cubic anisotropy possesses such a property.

Asymptotic models for piezoelectric stack actuators with thin metal inclusions

Winfried Geis[1,3], **Gennady Mishuris**[2], **Anna–Margarete Sändig**[1]
[1] IANS, Fachbereich Mathematik, Universität Stuttgart
Email: `geis,saendig@ians.uni-stuttgart.de`

[2]Rzeszów University of Technology, Department of Mathematics
Email: `miszuris@prz.rzeszow.pl`

[3] Robert Bosch GmbH, Automotive Electronics, Engineering Design Powertrain (AE/EDP5)

Cofired multi-layer actuators will be considered as composites. They consist of anisotropic piezo-elastic ceramic materials with stacked parallel electrodes. They are mathematically modeled as a quasi-static linear multi-field problem with appropriate boundary and transmission conditions [1]. The small relative thickness of the electrodes as well as the multi-field character of the problem provides difficulties in the numerical computation. Therefore, we formally derive an asymptotic model where the electrodes occur a s interfaces in the ceramic domain. Depending on the material parameters of the metal (unda maged and damaged case) the resulting transmission conditions are standard, nonstandard or even imperfect [2]. It turns out, that the stack actuator can be efficiently simulated by this asymptotic model which allows to compute the mechanical and electrical fields in real devices. Furthermore, the influence of the temperature field is demonstrated numerically [3].

References

[1] W. Geis, G. Mishuris, A.-M. Sändig, *Piezoelectricity in multi-layer actuators, Modelling and analysis in two and three dimensions.* Preprint IANS 2003/023, University Stuttgart.

[2] W. Geis, G. Mishuris, A.-M. Sändig, *Asymptotic models for piezoelectric stack actuators with thin metal inclusions.* Preprint IANS 2004/001, University Stuttgart.

[3] W. Geis, *Numerical simulation of linear models for piezoelectric stack actuators.* Preprint IANS 2005/007, University Stuttgart.

Simulation of Thin Piezoelectric Structures Using Higher Order Finite Elements

Andreas Hauck, **Manfred Kaltenbacher**, **Reinhard Lerch**
University of Erlangen-Nuremberg, Department of Sensor Technology
Email: andreas.hauck@lse.eei.uni-erlangen.de

Thin piezoelectric structures are important parts of active-noise cancellation devices and *smart structures*. In order to get an accurate prediction of the bending and vibration behavior, a suitable simulation model has to be chosen.
The traditional approach to model these structures is to use shell or plate elements combined with a laminated composite formulation. A major problem however is the choice of an accurate method to minimize the locking effects occurring in conjunction with thin structures. These are especially dominant when using linear finite elements but are present in quadratic ones as well.
An alternative is to use higher order finite elements (*p-FEM*), based on hierarchic Legendre polynomials. For a moderately high polynomial degree locking phenomena can be completely avoided. By approximating the displacements in thickness direction with a different polynomial order than in in-plane direction, the number of degrees of freedoms can be reduced significantly. In this work both methods have been implemented in order to compare the results as well as the efficiency for several thin structures.
Future work will deal with the full three-dimensional modeling of piezoelectric structures, where the anisotropic ansatz functions allow an efficient way to model thin structures as well as the transition to solid parts which require a three-dimensional model. As the new formulation is based on the full three-dimensional material law, nonlinearities can be applied in a straightforward manner without adapting it to the specific shell formulation.

Preisach operators and hysteresis modelling in piezoelectricity

Barbara Kaltenbacher
Universität Erlangen-Nürnberg, DFG-Nachwuchsforschergruppe am Lehrstuhl für Sensorik
Email: `barbara.kaltenbacher@lse.eei.uni-erlangen.de`

The Preisach model provides a well investigated and versatile tool for modelling rate independent memory effects. It enables to reproduce minor hysteresis loops and allows for direct generalizations from the scalar to the vectorial case. In the first part of this talk we discuss some of the properties of Preisach operators and present both known and new results on PDEs with hysteresis. Special emphasis is put on efficient numerical solution. While Preisach operators are well established in the context of magnetics, their use in piezoelectricity still poses many open questions. We propose an approach of combining the Preisach model, which is only phenomenological, with physically well-founded models based on thermodynamical laws as can be found in the papers by Kamlah, Mehling and respective coauthors. In the second part of this talk we present some ideas in this direction as well as first results of model fits to experimental data.

Poling of piezoceramic tubes

Bernd Laskewitz, Marc Kamlah
Forschungszentrum Karlsruhe, Institut für Materialforschung II
Email: kamlah@imf.fzk.de

Many piezoelectric actuator applications employ cylindrical geometries, where the electric field is applied in radial direction, leading to a radial polarization state. Furthermore, cylindrical geometries have been used extensively in experimental continuum mechanics in order to investigate homogenous multiaxial stress states.
In this paper, we discuss in detail the poling process of hollow cylinders made of ferroelectric ceramic material. The analysis is carried out by means of a finite element tool with appropriate constitutive models implemented for nonlinearily coupled ferroelectric and ferroelastic behavior. It is shown that in general a ferroelectric Bauschinger effect gives rise to an inhomogenous poling state. Furthermore, the results for a simple phenomenological constitutive model and a micromechanically motivated constitutive model are compared to each other.

Finite element computation of the constitutive behavior of PZT at electromechanical loading

Alexander Konstandin[1,2], **Sonja Daum**[3], **Volker Knoblauch**[2] **and Robert M. McMeeking**[4]

[1] Institute of Advanced Ceramics, Hamburg University of Technology

[2] Corporate Research and Development – Applied Research Materials, Robert Bosch GmbH
Email: `Alexander.Konstandin@de.bosch.com`

[3] Institut für Mechanik (Bauwesen), Universität Stuttgart

[4] Department of Mechanical Engineering, University of California

We compute numerically the constitutive materials behavior of a polycrystalline ferroelectric ceramic material (PZT) at combined multi-axial electromechanical loading. A phenomenological constitutive law for switching in ferroelectrics based on thermodynamics and concepts of plasticity theory is used to describe the materials response in predominant load cases. By developing an explicit (Forward Euler) algorithm in a finite element formulation we obtain a powerful tool unique to study complex models containing areas of heterogeneous polarization. The numerical results coincide convincingly with experimental data. A better efficiency of our tool has been achieved recently by implementing an implicit (Backward Euler) algorithm. Results of both formalisms are shown comparatively by means of a multi-axial load case.

Structural control of frame structures by piezoelectric actuation and sensing: theory and experimental verification

Michael Krommer[1], **Hans Irschik**[1] **and Daniel Huber**[2]

[1] Johannes Kepler University Linz, Institute for Technical Mechanics
Email: krommer@mechatronik.uni-linz.ac.at

[2] Linz Center of Mechatronics

The present paper is concerned with the modelling and control of frame structures, which are excited by an imposed 1-dimensional horizontal ground motion of a shaking table. For the control of the motion of such structures relative to the ground motion piezoelectric actuators and sensors are used. In general the relative motion will be composed of the relative motions of the floors plus additional vibrations of the highly flexible walls.

In the first part of this paper we concentrate on the control of the relative motion of the floors. A two degree of freedom mathematical model for a two story frame is derived, which takes into account axial forces, and a controller is designed based on the physical model. Furthermore, we consider structural damping in the equations of motion. For the control of the structure, piezoelectric patches are applied to the walls and used as both sensors and actuators. The arrangement of the sensors and actuators is collocated, with the sensors measuring an approximation for the relative motion of the floors. As the structure represents a port Hamiltonian system with dissipation with collocated sensors and actuators, a PD - controller can be used to control the relative motion of each floor. Experimental results are presented, in which the efficiency of the control strategy for the control of the relative motion of the two floors is validated.

In the second part we focus on the control of the vibrations of the flexible walls; especially, on those that do not result into any relative motion of the floors itself, because this latter relative motion is already controlled by the design we proposed in the first part. For that sake we need to design piezoelectric actuators that are capable to track arbitrary dynamic displacements of the walls. We base the theoretical solution of this inverse problem on an infinite dimensional beam model for a single story frame. We seek to distribute the actuation such that the walls perform a dynamic displacement proportional to the first eigenmode of a clamped-clamped beam. An exact theoretical solution is found, which requires the actuation to be distributed. In the experimental verification we use piezoelectric patches that are properly located and weighted in order to replace the required distributed actuation. A very good agreement between theory and experiment is obtained.

The physical model we used in the first part was a two degree of freedom model. With respect to the use of piezoelectric sensors to measure an approximation for the relative motion of the floors, it turned out that this model was not sufficiently accurate for a proper design of such sensors. For that sake we study the design of piezoelectric sensors for the measurement of the relative motion of the floors based on the infinite dimensional beam model for the single story frame in the third part of the paper. Again we are able to find an exact solution for a distributed sensing. From a practical point of view this exact solution needs to be approximated by the use piezoelectric patches. We present a method to calculate locations and weights for the individual patches such that the combined output of the patches represents a very good approximation for the relative motion of the floor. We validate this method by means of simulations only. An experimental verification of the sensor design in combination with closed loop control is planned for the near future.

Homogenization Techniques in Sensor/Actuator Applications

Tom Lahmer
Friedrich-Alexander-Universität Erlangen, Lehrstuhl für Sensorik
Email: tlahmer@lse.eei.uni-erlangen.de

Nowadays it is a common procedure to support the design process as well as material parameter adaption of sensors and actuators with numerical simulations.
Here, we consider sensors and actuators consisting of fine periodic structures which are repeated several hundreds of times, e.g. piezoelectric stack actuators or interdigital sensors. In order to obtain efficient algorithms, techniques of homogenization will be applied which approximate the finitely periodic structures.

The approach comprises two scales, a micro and a macroscopic one. In the microscopic scale the fine structure with periodic Dirichlet boundary conditions will be highly resolved on one exemplary micro cell. The macroscopic solution is superposed with local characteristics from the microcell, namely its eigenfunctions.

Numerical case studies for the above mentioned examples show the effects of the choice of the number of eigenfunctions on the micro cell, the mesh size on the macro scale and comparisons of the CPU times with the ones of a completely fine discretized body.

Elektroelastische Greensche Funktion des transversal-isotropen (hexagonalen) unendlichen Mediums

Thomas M. Michelitsch
Deptartment of Civil and Structural Engineering, The University of Sheffield
Email: t.michelitsch@sheffield.ac.uk

Die elektroelastische 4×4 Greensche Funktion eines piezoelektrischen hexagonalen unendlich ausgedehnten Mediums wird explizit in geschlossener Form angegeben. Die Ergebnisse werden mit Hilfe einer Residuenmethode gewonnen. Im Falle verschwindender piezoelektrischer Kopplung erhält man 2 wohlbekannte Ergebnisse: Der elastische Anteil repräsentiert dann die Krönersche elastische Greensche Funktion. Der dielektrische Anteil stellt in diesem Grenzfall das elektrische Potential (Lösung der Poisson-Gleichung) einer Einheitspunktladung dar. Die erhaltene Greensche Funktion erlaubt es, das elektroelastische Analogon des Eshelbytensors in einfacher Weise zu berechnen.

Interaction Problems of Metallic and Piezoelectric Materials with Regard to Thermal Stresses

Tengiz Buchukuri, David Natroshvili and OtariChkadua
Georgian Technical University, Tbilisi
Email: natrosh@hotmail.com

The recent years have seen a growing interest in the investigation of mathematical models of piezoelectric materials with regard to thermal effects. Here we study the following model problem related to engineering applications: Given is a three-dimensional composite consisting of a piezo-electric matrix with metallic inclusions (electrodes). An electric potential is prescribed to the metallic part of the composite. Due to the piezo property of the ceramic matrix and due to the thermal effects in the metallic and piezo-ceramic parts of the composite there appear thermomechanical and electric fields. It is required to describe the interaction of these physical fields and perform a rigorous mathematical analysis of the stress distribution in the composite. The main goals of the investigation are:
a) to derive a mathematical linear model of the physical problem and formulate appropriate boundary and transmission conditions,
b) to investigate the mathematical model and prove uniqueness, existence and regularity results,
c) to analyse distribution of thermomechanical stresses and electric fields,
d) to derive the corresponding asymptotic expansions near curves, where the type of boundary conditions change or the interfaces meet the exterior boundary,
e) to investigate the dependence of singularity exponents for the thermomechanical stresses and electric fields on the material parameters.
We consider geometrically regular composites, i.e., we assume that the metallic and piezo-ceramic parts of the composite have smooth boundaries.
Our approach is as follows. We use the Voigt's model and describe the physical problem by means of the strongly elliptic linear system of partial differential equations in the metallic and piezo-ceramic parts coupled by transmission conditions and endowed with mixed boundary conditions. The solutions to the mixed problem are constructed as layer potentials in the piezo-ceramic and metallic parts with unknown densities. The densities are to determine in such a way, that the interface and boundary conditions are satisfied. This reduces the original transmission problem to the equivalent strongly elliptic system of pseudodifferential equations involving pseudodifferential operators on sub-manifolds of boundaries of metallic inclusions and piezo-ceramic matrix.
Existence and regularity of solutions to the resulting boundary integral equations and the original transmission problem are analyzed in Sobolev-Slobodetski H^s_p and Besov $B^s_{p,t}$ spaces.
We show that the stress singularity exponents can be explicitly written by means of the eigenvalues of the principal symbol matrices of the corresponding pseudodifferential operators and study their dependence on the material constants.

Poling technologies of piezoceramics under electromechanical and thermal conditions

Michael Nicolai
Fraunhofer Institut für keramische Technologien und Systeme, (Fraunhofer IKTS)
Email: Michael.Nicolai@ikts.fraunhofer.de

In the last decades, piezoceramic materials were in focus of several investigations. In literature, various experiments related to non-linear properties of these materials are reported. External excessive electromechanical and thermal loads are driving forces for domain switching. Moreover, domain switching is identified as the main reason for overall nonlinear behavior of such materials. In order to better understand these effects, experiments are usually carried out by variation of one or two parameters like uni-axial stress or electric field. Also the relationship between temperature and poling electric field are well documented and discussed.

In future piezoceramic materials are expected to become more and more an integrated part of a complete component. Piezoceramic materials in alloy cast, resin transfer molding or laminated components will be underlaying multi-axial mechanical and thermal loading conditions. As a result of it, the ratio between rhombohedral and tetragonal perovskite type will be stress and temperature depending and in conclusion microscopic materials properties differ from the virgin stress free piezoceramic system. As a result, poling conditions will be completely different.

Based on simple ferroelectric and piezoelectric hysteresis numerical models, a more complex model for combined electromechanical and thermal conditions is of interest.

My personal intention for this workshop is: to evaluate and discuss existing models for electromechanical loading conditions and to find scientist working on similar problems.

About the development of strength criteria of piezoelectric interface corner configurations

Matthias Scherzer
TU Bergakademie Freiberg, Institut für Mechanik und Fluiddynamik
Email: Matthias.Scherzer@imfd.tu-freiberg.de

The development of modern adaptive materials is directed towards an exploitation of positive material properties of different material compounds in order to fulfil functional applications in an efficient manner. The reliability of these composite structures depends on the electro-mechanical behaviour of the embedded interface corner configurations. The mathematical modelling, the numerical solution of the corresponding boundary value problems and the formulation of strength criteria for these configurations represent very difficult problems. The given paper delivers a methodology for the formulation of strength criteria for piezoelectric interface corner configurations. The initial point of this research consists in the combined analytical and numerical approach for solving piezoelectric boundary value problems of interface configurations in smart structures presented in [1]. In addition, other related problems, concerning piezoelectrics are discussed.

References

[1] M. Scherzer and M. Kuna, *Combined analytical and numerical solution of 2D interface corner configurations between dissimilar piezoelectric materials*, International Journal of Fracture, 2004(127), pp. 61-99.

Mixed FEM for piezoelectric problems - recent work and difficulties

Arnd Meyer, Peter Steinhorst
Technische Universität Chemnitz, Fakultät für Mathematik
Email: peter.steinhorst@mathematik.tu-chemnitz.de

We want to present a numerical approach to simulate piezoelectric material behaviour by using Finite Elements. We use the method of adaptive mixed FEM for handling coupled mechanical and electric fields. The used solver (Bramble–Pasciak–CG) and preconditioner will be described briefly. Furthermore, ideas for error estimation needed by the refinement strategy are presented. Some actual problems using this method are addressed especially, such as the numerical instabilities in determining the derived quantities (as stress or dielectric field). Finally, first computational results from test examples using an experimental program complete the talk.

Participants

Jens Becker
Universität Stuttgart
Institut für Angewandte und Experimentelle Mechanik (IAM)
Allmandring 5 B, 70569 Stuttgart, Germany
Email: becker@iam.uni-stuttgart.de

Tengiz Buchukuri
A. Razmadze Mathematical Institute
Georgian Academie of Sciences
1 M. Alexidze Str., Tbilisi-75, Republic of Georgia
Email: t_buchukuri@yahoo.com

Otari Chkadua
A. Razmadze Mathematical Institute
Georgian Academie of Sciences
1, M. Alexidze str., Tbilisi-75, Republic of Georgia
Email: chkadua@rmi.acnet.ge

Winfried Geis
Universität Stuttgart
Institut für Angewandte Analysis und Numerische Simulation
Pfaffenwaldring 57, 70569 Stuttgart, Germany
geis@ians.uni-stuttgart.de
Robert Bosch GmbH
Automotive Electronics - Engineering Design Powertrain (AE/EDP5)
72703 Reutlingen, Germany
Winfried.Geis@de.bosch.com

Andreas Hauck
University of Erlangen-Nuremberg,
Department of Sensor Technology
Paul-Gordan-Str. 3/5, 91052 Erlangen, Germany
Email: andreas.hauck@lse.eei.uni-erlangen.de

Lukasz Janski
TU Bergakademie Freiberg
Institut für Mechanik und Fluiddynamik
Lampadiusstraße 4, 09596 Freiberg, Germany
Email: Lukasz.Janski@imfd.tu-freiberg.de

Barbara Kaltenbacher
Universität Erlangen-Nürnberg
DFG-Nachwuchsforschergruppe am Lehrstuhl für Sensorik
Paul-Gordan-Straße 3/5, 91052 Erlangen, Germany
Email: barbara.kaltenbacher@lse.eei.uni-erlangen.de

Marc Kamlah
Forschungszentrum Karlsruhe
Institut für Materialforschung II
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
Email: kamlah@imf.fzk.de

Alexander Konstandin
Robert Bosch GmbH
Forschung und Vorausentwicklung - Werkstoffe (CR/ARM1)
Postfach 10 60 50
70049 Stuttgart, Germany
Email: alexander.konstandin@de.bosch.com
Institute of Advanced Ceramics
Hamburg University of Technology
21071 Hamburg, Germany

Michael Krommer
Johannes Kepler University Linz
Institute for Technical Mechanics
Altenbergerstr.69, A-4040 Linz, Austria
Email: krommer@mechatronik.uni-linz.ac.at

Tom Lahmer
Friedrich-Alexander-Universität Erlangen
Lehrstuhl für Sensorik
Paul-Gordan-Str. 3-5, 91052 Erlangen, Germany
Email: tlahmer@lse.eei.uni-erlangen.de

Stefanie Mahlberg
Universität Stuttgart
Institut für Angewandte Analysis und Numerische Simulation
Pfaffenwaldring 57, 70569 Stuttgart, Germany
mahlberg@ians.uni-stuttgart.de

Arnd Meyer
Technische Universität Chemnitz
Fakultät für Mathematik
Reichenhainer Straße 39/417, 09107 Chemnitz, Germany
Email: a.meyer@mathematik.tu-chemnitz.de

Thomas M. Michelitsch
The University of Sheffield
Sir Frederick Mappin Bldg., Mappin St., Sheffield S1 3JD, UK
Email: t.michelitsch@sheffield.ac.uk

Gennady Mishuris
Rzeszów University of Technology
Department of Mathematics
35-959 Rzeszów, Poland
Email: miszuris@prz.rzeszow.pl

David Natroshvili
Georgian Technical University, Tbilisi
77, M. Kostava Str., Tbilisi-75, Republic of Georgia
Email: natrosh@hotmail.com

Michael Nicolai
Fraunhofer Institut für keramische Technologien und Systeme
(Fraunhofer IKTS)
Winterbergstr. 28, 01277 Dresden, Germany
Email: Michael.Nicolai@ikts.fraunhofer.de

Anna-Margarete Sändig
Universität Stuttgart
Institut für Angewandte Analysis und Numerische Simulation
Pfaffenwaldring 57, 70569 Stuttgart, Germany
saendig@mathematik.uni-stuttgart.de

Matthias Scherzer
TU Bergakademie Freiberg
Institut für Mechanik und Fluiddynamik
Lampadiusstraße 4, 09596 Freiberg, Germany
Email: Matthias.Scherzer@imfd.tu-freiberg.de

Peter Steinhorst
Technische Universität Chemnitz
Fakultät für Mathematik
Reichenhainer Straße 39/417, 09107 Chemnitz, Germany
Email: peter.steinhorst@mathematik.tu-chemnitz.de

Co-authors

Sonja Daum
Institut für Mechanik (Bauwesen)
Universität Stuttgart
70569 Stuttgart, Germany
Email: daum@mechbau.uni-stuttgart.de

Lothar Gaul
Universität Stuttgart
Institut für Angewandte und Experimentelle Mechanik (IAM)
Allmandring 5 B, 70569 Stuttgart, Germany
Email: gaul@mecha.uni-stuttgart.de

Daniel Huber
Linz Center of Mechatronics
Altenbergerstr.69, A-4040 Linz, Austria
Email: daniel.huber@lcm.at

Hans Irschik
Johannes Kepler University Linz
Institute for Technical Mechanics
Altenbergerstr.69, A-4040 Linz, Austria
Email: irschik@mechatronik.uni-linz.ac.at

Manfred Kaltenbacher
University of Erlangen-Nuremberg,
Department of Sensor Technology
Paul-Gordan-Str. 3/5, 91052 Erlangen, Germany
Email: manfred.kaltenbacher@lse.eei.uni-erlangen.de

Volker Knoblauch
Robert Bosch GmbH
Forschung und Vorausentwicklung - Werkstoffe (CR/ARM1)
Postfach 10 60 50
70049 Stuttgart, Germany
Email: volker.knoblauch@de.bosch.com

Bernd Laskewitz
Forschungszentrum Karlsruhe
Institut für Materialforschung II
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
Email: bernd.laskewitz@imf.fzk.de

Reinhard Lerch
University of Erlangen-Nuremberg,
Department of Sensor Technology
Paul-Gordan-Str. 3/5, 91052 Erlangen, Germany
Email: reinhard.lerch@lse.eei.uni-erlangen.de

Robert M. McMeeking
Department of Mechanical Engineering
University of California
Santa Barbara, CA 93106, USA
Email: rmcm@engineering.ucsb.edu

W. Geis, A.-M. Sändig (eds.)
Pfaffenwaldring 57
70569 Stuttgart
Germany
WWW: http://ians.uni-stuttgart.de

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