# Sixth
# Engineering Mechanics
# Symposium

## 24 - 25 November 2003
## Rolduc, Kerkrade

**Graduate School Engineering Mechanics**
**c/o Eindhoven University of Technology**

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# Contents

# Preface

The National Research School on Engineering Mechanics, a joint initiative of the Eindhoven and Delft Universities of Technology and the University of Twente, organizes on an annual basis the Engineering Mechanics Symposium. The aim of this symposium is to stimulate the communication and the exchange of information with respect to ongoing research in the field of Engineering Mechanics. To achieve this the program contains a keynote lecture by a leading expert in the field, topic sessions in relation to the selected research program of the Graduate School, poster presentations of actual research projects by PhD-students and a meeting of the senior academic staff.

The Sixth Engineering Mechanics Symposium takes place November 24-25, 2003 at Rolduc - Kerkrade.
In the opening session Prof. Ole Sigmund from the Technical University of Denmark at Lyngby, Department of Mechanical Engineering, will present a keynote lecture entitled: Topology optimization in wave-propagation problems.
Furthermore, two workshops are organized that partly run plenary and partly run in parallel. Topics of this years' workshops are:

- **Mechanics of Materials and Structures**
  organized by Leon Govaert (TU/e), Martin Tijssens (TUD) en Laurent Warnet (UT).
- **Dynamics, Control and Optimization**
  organized by Pascal Etman (TU/e), Fred van Keulen (TUD) en Ysbrand Wijnant (UT).

Firstly, plenary introductions to the Workshops are provided by the Workshop Organizers. Next, the Workshops run in parallel. Each Workshop consists of two parts, each containing 5 presentations by AIO's and Postdocs, followed by a discussion in which overall trends and conclusions are to be noticed. The duration of each of the AIO/Postdoc presentations is 20 min. Finally, there will be a plenary presentation of the trends and conclusions of the Workshops by the Workshop Organizers. For the best AIO-presentation within each workshop a prize will be awarded. Winners will be announced directly before the closing of the symposium on Tuesday, November 25th.

Additionally, there is a poster sessions in which about PhD-students participating in the Graduate School Engineering Mechanics present their current research project. In relation to these presentations a contest is organized in which an external jury selects the best three contributions. This year's members of the jury are Ir. F. Holwerda (NLR Amsterdam), Prof.Dr.Ir. J.B. Jonker (UT, Twente), Prof.Dr. R.M.M. Mattheij (TU/e, Eindhoven) en Dr.Ir. L.J. Sluys (TUD, Delft). Winners will be announced directly before the closing of the symposium on Tuesday, November 25th.

On Tuesday November 25th a meeting of the senior academic staff participating in Engineering Mechanics takes place. Topics regarding developments with respect to the "Sectorplan Wetenschap en Technologie", and the Netherlands Mechanics Committee as well as the inter-TU masters' program 'Fluid and Solid Mechanics' will be discussed.

This report contains more detailed information on the Sixth Engineering Mechanics Symposium. Included are the following sections:

- **Section 1:** Detailed program of the symposium.
- **Section 2:** Abstracts of the keynote lecture and introduction to the workshops.
- **Section 3:** Abstracts of presentations in the workshops.
- **Section 4:** Survey of poster presentations.

Individual poster presentations are collected in a separate report, which will be supplied at the start of the symposium. It also can be obtained from the Secretariat of the Graduate School. Furthermore, poster presentations are available through:

**http://www.em.tue.nl**

# 1

# PROGRAM

This section contains the detailed program of the Sixth Engineering Mechanics Symposium. Information on the keynote lecture and introductions to the sessions are presented in section 2. Abstracts of the presentations can be found in section 3.

# Program Sixth EM Symposium

**Monday, 24 November 2003**

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| 10.30-11.00 | Registration and Informal get-together **Conference room 3** |
| 11.00-11.10 | Opening of the Symposium by **Prof.Dr.Ir. R. de Borst** |
| 11.10-12.10 | Opening lecture: Topology Optimization in Wave-Propagation Problems<br>By **Prof.Dr. O. Sigmund**, Lyngby, Denmark |
| 12.10-12.30 | Introduction to Workshop 1: Mechanics of Materials and Structures<br>Mechanics of Materials and Structures by **Dr.Ir. M.G.A. Tijssens** |
| 12.30-12.50 | Introduction to Workshop 2: Dynamics, Control and Optimization<br>Engineering Optimization by **Prof.Dr.Ir. F. van Keulen** |
| 12.50-14.00 | Lunch |
| 14.00-15.00 | Workshops, part A |

| Workshop 1, Part A: **Conference room 1** | Workshop 2, Part A: **Conference room 2** |
|---|---|
| **R.P.M. Janssen** (TU/e)<br>A novel approach to predict the long-term mechanical behaviour of glassy polymers | **W. Ruijter** (UT)<br>Optimization of the Airbus A380 Vertical Tail Plane |
| **E.M. Viatkina** (TU/e)<br>Modelling of strain path change effects on the basis of dislocation structure evolution | **M.H.C. Hannink** (UT)<br>Optimised sound absorbing panels with quarter-wave resonators |
| **J. Fatemi** (TUD)<br>The Cosserat modeling of cancellous bone | **M.J. de Ruiter** (TUD)<br>Topology Optimization using a Topology Description Function Approach |

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| 15.00-15.30 | Break |
| 15.30-16.10 | Workshops, part A, cont'd |

| Workshop 1, Part A, cont'd:<br>**Conference room 1** | Workshop 2, Part A, cont'd:<br>**Conference room 2** |
|---|---|
| **V. Kouznetsova** (TU/e)<br>Computational homogenization for the multi-scale analysis of multi-phase materials | **K. Vervenne** (TUD)<br>Gradient-enhanced response surface building |
| **N.J.B. Driessen** (TU/e)<br>Mechanically induced collagen remodellling in cardiovascular tissues | **J.H. Jacobs** (TU/e)<br>Framework for sequential approximate optimization |

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| 16.15-18.00 | Poster Discussion Session I: **Conference room 4**<br>Presentation of current research projects, carried out by<br>**PhD-students and Postdocs** participating in Engineering Mechanics |
| 18.00-18.30 | Informal reception **Foyer** |

# Program Sixth EM Symposium

| Tuesday 25 November 2003 | |
|---|---|
| 09.00-10.40 | Workshops, Part B |

| Workshop 1, Part B:<br>**Conference room 1** | Workshop 2, Part B:<br>**Conference room 2** |
|---|---|
| **C. Iacono** (TUD)<br>Paramaters estimation of continuum damage models | **A.P.D. Weustink** (TUD)<br>Optimal Spreading of Fiber Bundles for Thermoplastic Impregnation |
| **R.H.W. ten Thije** (UT)<br>Finite element simulation of draping with non-crimp fabrics | **F.X. DeBiesme** (TU/e)<br>Faster BEM for vibroacoustics optimization |
| **R. Loendersloot** (UT)<br>Permeability Prediction of Non-Crimp Fabrics Based on a Geometric Model | **W.J. Dijkhof** (TU/e)<br>Dealing with uncertainty in structural accoustic optimization |
| **M. Langelaar** (TUD)<br>Computational Modelling of R-phase Transformation Pseudo-Elasticity in NiTi | **R.R. Waiboer** (UT)<br>Parameter Optimization Techniques for Robot Identification and Realistic Dynamic Simulation |
| **H.R. Pasaribu** (UT)<br>Friction reduction by adding copper oxide into alumina and zirconia ceramics | **R.J. Hesseling** (TU/e)<br>Control design for occupant restraint system accounting for constraints |

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| 10.40-11.10 | Break |
| 11.10-11.30 | **Conference room 1**<br>Presentation of results of Workshop 1 by Workshop Organizers |
| 11.30-11.50 | Presentation of results of Workshop 2 by Workshop Organizers |
| 11.50-12.10 | Announcement of the winning contributions in the AIO/Postdoc Presentation contest and in the Poster contest |
| 12.10-12.15 | Closure |
| 12.15-13.25 | Lunch |
| 13.40-14.40 | Assembly of Project Leaders EM **Conference room 2** |
| 16.00-19.30 | Meeting of EM Advisory Board (near Eindhoven) |

# 2

# KEYNOTE LECTURE

## and

# INTRODUCTION TO THE WORKSHOPS

This section contains abstracts of the keynote lecture by Prof. Ole Sigmund, Technical University of Denmark, Lyngby, Denmark and introductions to the workshops “Mechanics of Materials and Structures” and “ Dynamics, Control and Optimization” by the session organizers.

## Keynote lecture

# TOPOLOGY OPTIMIZATION IN WAVE-PROPAGATION PROBLEMS

Prof. O. Sigmund and J. S. Jensen

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We consider topology optimization of structures and materials subjected to wave-loads. By distributing one or more materials in a design domain, one may design optimal loud speakers, acoustic or optic lenses, wave guides, band gap materials and others. A band gap material is a multi-phase material that inhibits wave-transmission in certain frequency ranges - so-called band gaps.

Acoustic, elastic shear and planar electromagnetic waves are all modelled using the Helmholtz equation. Taking basis in problems modelled by the Helmholtz equation we develop topology optimization formulations that can be used to minimize or maximize local wave magnitude or propagation energy. Contrary to most other topology optimization problems haven been considered so far, a volume constraint is not necessary. This is due to the observation that homogeneous materials or structures cannot be used to minimize or maximize wave magnitudes and therefore a composite structure with unknown filling fraction will always be better than the homogeneous structure. In order to optimize responses in wider frequency ranges we formulate the optimization problems as max-min problems.

After a description of theory and implementation aspects, we show applications such as the design of acoustic horns and lenses, resonators, wave guides, sound walls, filters and optical devices. We expect to have experimental verifications of the optical devices ready at the time of the presentation.

# Workshop 1

# Mechanics of Materials and Structures

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Innovations in technological applications increasingly demand that the properties of the materials are exploited to the fullest extent. Classically, materials used in engineering applications are used up to their elastic limit. The increased understanding of material behavior starting from the initial linear elastic regime up to and including failure has facilitated the design of technological applications in which the entire load-carrying capacity of materials is being used. The accurate simulation of material behaviour still plays a central role in this development. The research groups at TUD, TUE and UT all contribute, via various research directions, to a continuously increasing understanding of material behaviour at all length scales.

The accurate description of material behaviour on a specific length scale (say, the macro level) often requires an analysis of all deformation stages (linear and non-linear up to failure) on a smaller length scale (say, the micro level). The analysis of the micro level requires an accurate knowledge of the structure of the material as well as constitutive models for all relevant physical processes on this level. Depending on the specific application, research paths may focus on (I) an adequate simulation of the structure of the material, (ii) the formulation of material models that capture the relevant physical phenomena on the micro level, (iii) homogenisation procedures that facilitate the formulation of constitutive models on the macro level in which all relevant physical phenomena are accounted for, (iv) the identification of material parameters that occur in the material models and (v) the proper use of the model in the design of technological applications. The workshop will address all these topics through selected contributions from all participating universities.

The simulation of the structure of man-made materials, for example non-crimp fabrics, is addressed in the contribution by ten Thije. This work focuses on the formulation of a finite element model that simulates the draping process of the fabric. The outcome of the model, i.e., the geometry and the final orientation of the fibre bundles, may be used to predict problem regions during the draping process. Once the structure of a material on the relevant micro level is determined, constitutive relations are formulated that capture all relevant physical phenomena. Based on the predicted geometry, Loendersloot et al. are able to apply a model built for the prediction of the permeability of non-crimp fabrics which facilitates a better simulation of the mould filling during the production process. The contribution from Janssen et al. addresses the formulation of a single parameter material model for glassy polymers based on the Leonov model that accounts for progressive aging. The contribution from Viatkina et al. focuses on the formulation of a dislocation cell structure model that is able to describe the changes in dislocation structures as a result of strain path changes. The contribution of Driessen et al. focuses on the formulation of a material model for biological tissue that both accounts for and predicts the change in orientation of the fibrillar structure of the material.

The analysis on the micro-level is followed by a formulation of models on the macro level in a way that preserves all relevant information for this level. The workshop provides two contributions that focus on this transition. The contribution from Fatemi and Van Keulen focuses on the formulation of a constitutive model for cancellous bone based on a Cosserat continuum model. The transition to the macro level is done a priori using either a Cosserat homogenisation approach or an optimisation-based approach. These approaches yield the elastic Cosserat moduli for the macro level. The contribution from Kouznetsova et al. addresses a numerical homogenisation approach that facilitates the homogenisation of the relevant micro level processes in cases where the scale of the micro level is not negligible to the scale of the macro level.

The design of innovative technological applications relies on the formulation of predictive macro level material models. The analysis of the micro-level and subsequent transition to the macro-level provides all relevant data needed for the specific case being considered. Another approach is the formulation of a generic material model applicable to a class of materials and phenomena on the macro level and the subsequent determination of material parameters that best apply to a specific problem. The contribution to the workshop from Iacono et al. addresses this issue. Their work focuses on the formulation of an inverse problem that yields the best set of model parameters through the minimization of a function that captures both local and global information of the deformation processes. The contribution of Langelaar and Van Keulen focuses on the formulation of a material model for a specific class of martensitic phase transformations, i.e. the R-phase transition in NiTi, suitable for the design of micro-actuators. Finally, the contribution from Pasaribu et al. shows an example of micro-macro property relation in an experimental study on friction reduction in alumina and zirconia ceramics by the addition of copper oxide.

# Workshop 2

# Engineering Optimization

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Design optimization aims to find the best design within the available means. This can be mathematically formulated as: find the set of design variable values that will minimize some objective function subject to a set of constraints. Early optimization activities in the engineering design field were mainly restricted to the use of analytical models. In such a setting, engineers had to cast a design problem into an analytical analysis model, which had to be complemented with a definition of the optimization problem. Obviously, only limited complexity could be addressed. As soon as computers became available in the engineering field, both researchers and engineers have tried to use computer models in combination with mathematical optimization algorithms. The interest to combine, e.g., finite element method and optimization is nicely demonstrated by early research on design sensitivities in the seventies. Despite its potential, computer-based optimization became a mature design tool only recently, i.e. during the last decade. Among the industrial pioneers who adopted optimization as a standard design tool are the aerospace and automotive fields. Due to limited computer resources, early computer-based optimization attempts had to rely on a limited number of design evaluations. The availability of faster computers has changed the engineering optimization field significantly.

Today, design optimization methods are subject of ongoing research. Motivated by the increasing interest by industry, aspects being addressed are their efficiency, versatility and robustness. Both non-gradient and gradient-based methods receive substantial attention. Interesting in this aspect is that methods relying on brute force computing are becoming very popular and are often used in practical applications. Adjacent to the research on optimization methods, design sensitivity analysis still attracts many research activities. However, the focus has somewhat shifted towards the automated or computational derivatives. In the engineering field, topology optimization, reliability-based and multi-level optimization are main research issues. Topology or layout optimization became a hot research item in the nineties and found its way very quickly to industry. Reliability-based optimization is recognized more and more as the preferred technique, although computer resources still limit its practical application. The multi-level techniques are still in their infancy although they are mandatory for large-scale industrial optimization tasks.

Within the Engineering Mechanics graduate research school, most of the activities as sketched above are being addressed to some extent. Main attention and efforts are on the modeling aspects. But a growing number of PhD projects within the EM research program is dealing with design optimization subjects, including sensitivity analysis, topology optimization, reliability-based optimization, simulation-based optimization, multi-level design optimization, metamodeling techniques, and combined optimal design and optimal control.

Accordingly, the workshop addresses the following two main themes:

1) *Method development and application*
2) *Design and analysis tools for optimization*.

# 3

# ABSTRACTS OF PRESENTATIONS

This section contains abstracts of presentations at the Sixth Engineering Mechanics Symposium. Abstracts are in alphabetic order on the (first) author. Abstracts of the keynote lecture and an introduction to the workshops are presented in section 2.

# Faster BEM for vibroacoustics optimization

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The Boundary Element Method forms an important computational tool for designing low noise products. Optimization of structures for vibroacoustics is a classical situation where a lot of simulations (mainly using the Boundary Element Method or BEM) have to be done.
Currently a lot of research focuses on computational ``tricks'' to solve bigger problems faster and using less memory. In contrast, our research aims at modifying the core of the method using physical assumptions. We focus on an efficient discretization of the Kirchoff-Helmholtz equation, which is the foundation of acoustical BEM. A special treatment of the variables (Lumped Parameters) proved to be very efficient in terms of assembly speed and in terms of reduction of the degrees of freedom. The Lumped Parameters have been studied both physically and mathematically.
As an example, a sound power simulation was performed on a force excited plate. It showed a time reduction of a factor 12.

## References

[1.] F.X. DeBiesme and J.W. Verheij and G.Verbeek, Lumped Parameter BEM for faster Calculations of sound radiations from structures, ICSV 10, 2003
[2.] F.X. DeBiesme, A.A.A Peeters and J.W. Verheij, On speed and accuracy of Lumped Parameter BEM, ICSV 10, 2003

# Dealing with uncertainty in structural acoustic optmization

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## Introduction

Computational analysis and optimization are important needs in designing low noise products. Our research concentrates on dealing with the consequences of structural uncertainties, when optimizing the vibrational (or sound radiation) behavior of mechanical structures. A satellite arm may serve for a case study. It is used to carry vibration sensitive equipment and therefore the vibration transmission should be minimized [1]. However, small uncertainties in e.g. joint positions of the rods will cause that each physical realization will show different minima [2].

## Methodology

Monte Carlo Simulation can be used as a reference method for determining the relevant statistics. However, the research focusses on other methods, which are much less demanding in terms of required computational time. Especially we concentrate on perturbation methods [3,4] in combination with Component Mode Synthesis [5], because: (1) these methods are computationally efficient, (2) they can be combined with existing FEM packages and (3) some structural components can be regarded as deterministic.

## Results

Two perturbation methods are considered: (1) Taylor series and (2) Local Modal Perturbation method. The first one is implemented in matlab (using Ansys FE models as input) and is combined with Component Mode Synthesis. The second one is currently being implemented. A comparison of both methods with a Monte Carlo Simulation will be presented.

## Reference

[1] A.J. Keane, A.P. Bright, “Passive Vibration control via unusual geometries: Experiments on model aerospace structures”, Journal of Sound and Vibration, 190(4), pp. 713-719, 1996.
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[4] B.R.Mace, P.J.Shorter, “A local modal/perturbational method for estimating frequency response statistics of built-up structures with uncertain properties,” Journal of Sound and Vibration, 242(5), pp. 793-811, 2000.
[5] R.R.Craig Jr., “Substructure Methods in Vibration”, Transactions of the ASME, 117(6), pp. 207-213, 1995.

# Mechanically induced collagen remodelling in cardiovascular tissues

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Tissue engineering represents an alternative technology to overcome the disadvantages of the currently used tissue replacements in the human body. The concept of tissue engineering is based on seeding autologous cells onto a biodegradable carrier (the scaffold) and delivering the appropriate environmental cues (the stimuli) to culture the construct. The goal of tissue engineering is to create a functional living tissue that resembles the native tissue and has the ability to grow, repair and remodel in response to changes in the mechanical environment. Successful functional tissue engineering of load bearing structures requires that the engineered construct mimics the (mechanical) properties of the native tissue to fulfill the functional demands. It has been shown that mechanical conditioning (e.g. in a bioreactor) stimulates matrix production, enhances tissue organisation and improves the mechanical properties of engineered constructs. Understanding tissue adaptation and remodelling is essential to optimise these conditioning protocols and to improve the mechanical integrity of the tissue engineered structures. Because of the complex interaction between tissue remodelling and the mechanical condition within the tissue, mathematical models are desired to study this interrelation. As the mechanical properties of the tissue are mainly determined by a well-organised collagen architecture, the model should focus on remodelling of the collagen network.

The objective of this study is to predict the evolution of collagen fibre content and orientation in cardiovascular structures. A theory capable of 1) describing the mechanical state within the tissue and 2) accounting for the effects of fibre remodelling on the tissue’s constitutive behaviour, is presented. The tissues are modelled as an incompressible fibre reinforced material. The constitutive law for this transversely isotropic composite material has structural parameters to account for the fibre orientation and the fibre content [1]. We hypothesise that the collagen fibres align with preferred directions, situated in between the principal stretch directions. The orientation of these preferred fibre directions depends on the magnitude of the principal stretches.

In order to test our hypothesis, the theory is applied to study collagen remodelling in arteries and aortic heart valves [2,3]. The artery is modelled as a two-layer thick-walled cylinder and is inflated by an internal pressure and stretched longitudinally. The predicted fibre directions represent helical paths and resemble the experimentally measured collagen architecture in arteries [4]. The aortic valve is modelled as a leaflet with uniform thickness and is loaded by a transvalvular pressure in the diastolic (i.e. closed) phase. The model predicts a branching collagen network, which resembles the macroscopically visible hammock-type fibre architecture [5].

## References

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[2] Driessen et al., 2003, Journal of Theoretical Biology, in press.
[3] Driessen et al., 2003, Journal of Biomechanical Engineering, submitted.
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# The Cosserat modeling of cancellous bone

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Mechanical modeling of bone is of interest to many applications in orthopedic biomechanics such as analysis of the skeleton, analysis and design of orthopedic devices, analysis of tissue growth, remodeling and degeneration. Bone tissue is a natural composite, which at different levels of scale exhibits fibrous, porous, and particulate microstructural features. The microstructures are responsible for the macroscopic material properties of bone. Continuum models of bone based on the classical elasticity provide good estimates for the overall mechanical properties when the macroscopic length scale (e.g. the smallest typical length scale of the deformation pattern) is much larger than the material length scale. However, in regions of high strain gradient, e.g. near a hole or near the bone-prosthesis interface, the two length scales become comparable and the classical continuum assumption is violated.

A general approach to overcome the above limitations is provided by the extension of the classical continuum model to generalized continuum models, which intrinsically introduce an internal length scale to the constitutive model. Cosserat (micropolar) continuum theory is one of them. In the Cosserat representation, materials are idealized at each point to possess individual rigid directors. The kinematics of a Cosserat continuum is enriched by the rotation of these directors. Therefore, material points can possess microrotations in addition to the classical displacement field. Deformation of Cosserat materials are then constructed by superposing the classical macroscale deformations with the local (microscale) deformations related to the rotation of directors. One of the major problems involved in relating this theory to observed material behavior is the determination of the Cosserat constitutive coefficients.

This work addresses the Cosserat modeling of cancellous bone. Two different methods for derivation of the Cosserat elastic moduli of cellular solids are presented. Both are based on the micromechanical analysis. The first method is based on a Cosserat homogenization approach [1,2]. Kinematic boundary conditions are applied to a representative volume of a twodimensional cancellous bone to determine the Cosserat elastic moduli. It is shown that application of some boundary conditions leads to the boundary layer effects. To account for these effects, an optimization-based identification method for the derivation of Cosserat elastic moduli of cellular solids is proposed [3]. In this method, the identification procedure is formulated as an optimization problem. An error function that expresses the difference between the strain energies of the micromechanical model and its equivalent Cosserat continuum model is minimized for a carefully selected set of kinematic boundary conditions.

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[3] Fatemi, J. and van Keulen, F., "Identification of elastic constants of micropolar solids using an optimization approach," Proceedings of the 5th World Congress on Structural and Multidisciplinary Optimization, Venice, Italy, May 19-23, 2003.

# Optimised sound absorbing panels with quarter-wave resonators

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In modern aircraft, boundary layer induced noise is known to dominate cabin noise at cruise conditions. In order to improve the environmental comfort of the passengers with respect to this boundary layer induced noise, the present research focusses on the optimisation of sound absorbing trim panels with quarter-wave resonators. The research is carried out as part of the EU project FACE (Friendly Aircraft Cabin Environment).

By varying the dimensions of the quarter-wave resonators, different levels of sound absorption can be obtained in different frequency ranges. Optimisation of these resonator dimensions will result in a sound absorbing trim panel that optimally reduces the cabin noise in the dominant frequency range.

The viscothermal wave propagation of the air inside the resonators is efficiently and accurately described by the so-called low reduced frequency model. Using this model, absorption coefficients can be calculated for different configurations. In order to be able to satisfy any desired absorption level within a specified frequency range, an optimisation algorithm has been implemented. Results of optimisations in the frequency ranges of 500-1000 Hz and 1000-2000 Hz show that almost maximum absorption is obtained over the entire frequency ranges. Experimental validation of the numerically predicted optimal configurations is performed by means of impedance tube measurements.

Once the optimised configurations have been validated, a sound absorbing trim panel will be designed by tuning to a sound spectrum measured in a modern aircraft. In this way high absorption levels can be obtained for frequencies with high sound levels, whereas lower absorption levels are allowed for frequencies at which sound absorption is not needed.

Another important issue that is subject of investigation is the practical implementation of the resonators. Practical aspects as available space and requirements for weight and fire resistance play an important role in the aircraft industry. To reduce the thickness of the trim panels, various resonator concepts have been worked out. Tube resonators can, for example, be placed parallel to the surface of the panel, or flat resonators can be applied.

## Acknowledgements

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# Control design for occupant restraint system accounting for constraints

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## Introduction

A vehicle restraint system restrains the occupant in the event of a crash. It has the objective to reduce the occupant injuries as much as possible. Examples of such systems are the safety belt and the airbag. In most modern vehicles, algorithms decide, after a crash is detected, which operation mode for the safety belt and the airbag is the most appropriate, considering estimations of crash and occupant characteristics, e.g., [1].

In this presentation, an approach is presented to arrive at a control algorithm to continuously manipulate the restraint system during the crash. Such an approach can be used as an expedient during the design of a restraint system, and/or can be the basis for the control of future restraint systems.

## Methodology

The available non-linear numerical finite element and multibody model of a crash is too complex, lumpy and time-consuming for control design purposes. Hence, it is tried to describe the relevant phenomena and system dynamics with easy to handle, linear and constant models. For that purpose, models are identified based on i) measurements on the input and output of the numerical model [2,3] and ii) insight in the relevant phenomena and system dynamics [4,5].

A model predictive controller is constructed that makes use of the identified models, and that accounts for constraints on the manipulated variables of the restraint system, like the maximum load on the occupant. In addition, constraints on the motion of the occupant as, for instance, the distance to the steering wheel, are accounted for.

## Results

A model predictive controller is presented to manipulate the force in the belt for the driver, such that the maximum chest deceleration of the driver is as low as possible. The predictive controller accounts for constraints on the allowable belt force and on the occupant motion. In the presented approach, the airbag is not controlled. In comparison with the base line restraint system, a reduction of the maximal chest deceleration of 46% is obtained.

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# Parameters estimation of continuum damage models

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In the Structural Mechanics field researchers are interested in developing numerical models that can simulate and predict the real behaviour of materials and structures. However the reliability of these models heavily depends on the correct determination of the model parameters. Parameters directly related to measurable quantities may be identified during laboratory test, while the remaining parameters may be estimated by solving an inverse problem.

The kernel of an inverse problem is the definition of a functional expressing (in different ways) the difference between the numerical solution, obtained by the model, and the real observed behaviour of the structure. Some measurable quantities may be measured in the real case and compared with the corresponding computational quantities that depend on the model parameters. The solution of the inverse problem is the parameter set that corresponds to the minimum of the functional.

Three fundamental aspects in the parameter identification (inverse) problem must be considered: the accuracy, the uniqueness and the identifiability of the parameters. The ill-posedness of the inverse problem may lead to different parameter sets with the same accuracy of data fitting. The type of measurable quantities (experimental information) used in the definition of the functional plays a key role: not only global data, as the load-deformation curve of the structure, but also local information, as deformations in the cracked process zone, should be considered.

The parameters identification problem regarding the gradient-enhanced (non-local) continuum damage model is considered as study case. In particular the estimation of the internal length parameter is of prime interest. The experimental data of tensile size effect tests of dog-bone shaped specimens are used for this purpose. In order to examine the mentioned aspects two inverse techniques are used and compared: the Kalman Filter (KF) technique and the K-Nearest Neighbors method (KNN).
The KF technique, in the framework of probability calculus that allows to consider both the uncertainties of the model and of the experimental measurements, takes into account also an a priori guess of the parameters. On the other hand, the KNN method is a derivative free procedure that not only selects the best parameters set, but also can identify trends and promising regions in the parameters space. This offers the advantage of parallel runs of different forward problems.

Finally the solution of the parameter identification problem is studied *during* the fracture process in order to investigate the possibility of variation of the internal length scale not only with the characteristic size but also with the damage state of the specimen.

# Framework for sequential approximate optimization

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An object-oriented framework for Sequential Approximate Optimization (SAO) is proposed. SAO methods are used especially when a computationally expensive and/or noisy simulation model is part of the optimization loop. In order to assure reasonably fast optimization, the number of calls to the simulation model, i.e. the number of evaluations of objective function and constraint functions, has to be reasonably small. Therefore, SAO methods build explicit approximations for objective and constraints using a restricted number of simulation evaluations in a sub region of the total design space. The resulting approximate optimization sub problem is explicit and can be easily solved within the search sub region using any suitable mathematical programming algorithm. A move limit strategy (or trust region strategy) is used to successively define the sequence of search sub regions in which approximate optimization sub problems are built and solved. Each approximate optimum design is evaluated using the simulation model. When no further or minimal improvement is obtained, the SAO process should stop.

The newly developed SAO framework aims to provide an open environment for development and implementation of SAO strategies. The key idea is to distinguish three basic layers: an optimization problem layer, an SAO sequence layer, and a numerical routines layer. The problem layer specifies the optimization problem, including the simulation model for evaluation of objective function and constraints. The sequence layer specifies the sequence of steps in the SAO approach. The routine layer represent numerical routines used by the SAO approach as 'black-box' functions with pre-defined input and output, e.g. from external software libraries. The routines carry out specific computational tasks, such as the determination of a design of experiments, a linear regression analysis, or the solution of a nonlinear programming problem. The framework enables the user to (re-) specify or change the SAO dependent modules, which is generally not possibly in most available SAO implementations. This is highly advantageous since many SAO approaches are application domain specific due to the type of approximation functions used.

The framework gives an easy access to the contents of each three layers. This is realized in an object-oriented framework developed in Python. The presentation describes the layout and data classes of the developed framework. The framework starts from some predefined SAO sequence classes as well as a toolbox of basic numerical routines to carry out basic steps in the SAO sequence. On this basis, the framework enables to redefine or implement new SAO sequences, and allows introducing other (third-party) numerical routines not available from the framework toolbox. The twenty-five bar transmission tower design problem is used as illustration.

# A novel approach to predict the long-term mechanical behaviour of glassy polymers

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At present, shape and dimensions of polymer products required to fulfill their mechanical requirements are selected through experience during prototyping or experience from applications of the same kind. As an experimental investigation would be very time and costexpensive, a numerical model able to predict the long-term behaviour under loading can be considered as the key to more specific product dimensions. The compressible Leonov-model has already proved to predict effectively the strain localisation of glassy polymers during (short-term) uni-axial tensile testing [1]. Since similar samples show similar failure behaviour during long-term creep and fatigue loading, the same numerical approach is applied to predict the time to failure under long-term loading. In this study on polycarbonate, it is shown that the creep and fatigue loading can be accurately predicted from the intrinsic properties, determined by compression testing.

Firstly, an investigation to the model and its abilities in the case of creep loading is performed. It showed that, in the range where experimentally ductile failure (necking) is observed, the compressible Leonov model makes a very accurate prediction for the experimental time-to-failure. However, beyond the ductile-to-brittle transition, at lower stress levels, the model overestimates the time-to-fracture. This transition showed to be strongly dependent on molecular weight. The higher the molecular weight, the later the ductile-tobrittle transition is observed. Moreover, during the loading of polycarbonate its intrinsic properties, and hence its failure behaviour, alter as a result of progressive ageing. Therefore, an improvement on the model is made by the incorporation of the influence of progressive aging on the intrinsic deformation behaviour.

For the description of the progressive ageing, an evolution of the yield stress is implemented as a function of ageing time, temperature and applied load. In the constitutive model this evolution is represented by the state parameter ‘Da’, which uniquely describes the amount of “stress overshoot” during yielding compared to the fully rejuvenated state. As a result, the model proved to be capable to accurately predict the influence of initial thermal history on creep-rupture. Preliminary numerical results of fatigue loading seem to predict the experimental response in a same accurate manner as well.

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# Computational homogenization for the multi-scale analysis of multi-phase materials

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Most of the materials produced and utilized in industry are heterogeneous on one or another spatial scale. Typical examples include metal alloy systems, porous media, polycrystalline materials and composites. The (possibly evolving) size, shape, physical properties and spatial distribution of the microstructural constituents largely determine the macroscopic, overall behaviour of these multi-phase materials. Consequently, these microstructural influences are important for the production routes and the life performance of the material and products made thereof.

To predict the macroscopic behaviour of heterogeneous materials various homogenization techniques are typically used. However, most of the existing homogenization methods are not suitable for large deformations and complex loading paths (e.g. encountered during forming operations) and cannot account for an evolving microstructure (e.g. due to phase transformations). To overcome these problems a computational homogenization approach has been developed, which essentially provides a numerical framework for obtaining the stress-strain response at a macroscopic material point based on the behaviour of the underlying microstructure. Existing (first-order) computational homogenization techniques prove to be a valuable tool in retrieving the macroscopic mechanical response of evolving non-linear multi-phase materials. However, their applicability is generally restricted to cases where the size of the material microstructure is negligible with respect to the characteristic wave length of the macroscopic deformation field.

In order to deal with these limitations, a novel second-order computational homogenization procedure has been proposed [1-3] as an extension of the first-order framework. The most important property of the second-order computational homogenization method is, in fact, that the relevant length scale of the microstructure is directly incorporated into the description on the macrolevel via the size of the representative cell. This allows to describe certain phenomena that cannot be addressed by the first-order scheme, such as size effects and macroscopic localization. Furthermore, the second-order framework allows the modelling of surface layer effects via the incorporation of higher-order boundary conditions. Higher-order continuum modelling becomes considerably easier with the use of the second-order computational homogenization scheme because the second-order response is directly obtained from a microstructural analysis, rather than by closed-form constitutive relations, which are difficult to formulate and which contain a large number of parameters.

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# Computational Modelling of R-phase Transformation Pseudo-Elasticity in NiTi

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Shape memory alloys are promising materials for microactuation applications. In comparison to other actuator materials, they offer the highest specific work output, and are capable of generating relatively large strains. Near-equiatomic NiTi alloys are the most widely used shape memory alloys, due to their superior properties. The shape memory effects in these alloys are caused by a diffusionless solid state phase transformation between a cubic austenite (A) lattice and a monoclinic martensite (M) lattice of lower symmetry. In the martensite state, the material can accommodate some strain by reorientation of variants. In nickel-rich NiTi alloys, also a rhombohedral (R) lattice is possible: this is the so-called R-phase. In contrast to the A-M transformation and martensitic transformations in most other shape memory alloys, the A-R transformation has a very small hysteresis, which makes it particularly attractive for actuator applications.

The phase transformation in shape memory alloys is influenced by both temperature and stress state, which leads to various effects. At low temperatures, an apparent plastic strain can be recovered by heating: this is called the one-way effect. At higher temperatures, a stress-induced transformation takes place during loading, and is reversed during unloading. This makes that the material seems to be capable of large elastic strains: this effect is called transformation pseudo-elasticity. Due to the temperature-dependence of the transformation, this effect also can be used for actuation.

In this work, the focus is on the transformation pseudo-elasticity effect based on the austenite- R-phase transformation in NiTi, because of its suitability for microactuator applications. Due to the complexity of the material behaviour, the design of actuators based on this effect is challenging. Our aim is to explore the applicability and effectiveness of design optimization techniques for this class of actuators. Therefore in the computational modelling attention is paid not only to the adequate representation of experimental data, but also to the suitability of the model for design optimisation.
An important issue in design optimisation is the availability of gradients with respect to the design variables. More efficient optimisation algorithms can be used when such gradients, known as design sensitivities, can be computed cheaply. It will be shown that in the case of Rphase transformation pseudo-elasticity it is possible to formulate an approximate constitutive model in a history-independent way, which significantly reduces the complexity of the computation of design sensitivities. Next to a discussion of the formulation of the computational model, also its practical use will be illustrated by means of an example.

# Permeability Prediction of Non-Crimp Fabrics Based on a Geometric Model

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Resin Transfer Moulding (RTM) has proven to be a cost effective production method for nearnet shaped products with a high accuracy and a high reproducibility. It makes RTM suitable for the manufacture of complex shaped products. The applicability of non-crimp fabrics (NCFs) in RTM offers both lower cost and improved through-thickness properties with no significant drop in in-plane properties compared to woven fabrics, due to better crimp and drapeability properties.

Accurate flow simulations are an essential tool in finding the optimal process parameters, in particular for complex shaped structural components as applied in the aircraft industry. One of the most critical parameters in the mould filling simulations is the permeability of the fibre preform, which is in essence a geometric quantity. Geometrical changes, such as compaction and drape affect the permeability. This research aims to predict the permeability on a local level. The local permeability depends on the geometrical features of non-crimp fabrics and the influences of fabric deformation on these features.

The proposed geometric model is based on the distortions induced by the stitches penetrating the uni-directional fibre layers. Fibres are forced aside by the needle penetrating the individual layers during the production cycle. The fibres enclose the thread, which is left behind by the needle, forming a double wedge shaped distortion in the plane of the fibres in each layer. The distortions in each layer are oriented in the direction of the fibres and form flow channels, which determine the permeability of the fabric. Flow channels in the different fabric layers are connected to each other in overlapping regions, creating a network of flow channels. The distortions, referred to as Stitch Yarn Distortions (SYD), are defined in [1,2,3].

The dimensions of the Stitch Yarn Distortions depend on a number of variables, partly related to manufacturing parameters and partly to fabric and stitch yarn properties. It is not clear yet how these parameters affect the dimensions of the SYD. The width of the SYD is linked to the stitch yarn diameter assuming a linear relationship, where the proportionality constant is treated empirically.

Investigations on different types of fabrics revealed that the dimensions of the SYDs are distributed values. It is also shown that the dimensions as well as the distribution change under deformation of the fabric [2,3].

The distribution of the dimensions complicates the permeability prediction. As a consequence, the predicted permeability is an averaged value plus a distribution. Moreover, a SYD network, having a certain SYD size distribution, will have to be analysed, rather than a single SYD. This urges the development of fast solution algorithms for the fluid flow in this network. A multigrid solver is implemented for this purpose.

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# FRICTION REDUCTION BY ADDING COPPER OXIDE INTO ALUMINA AND ZIRCONIA CERAMICS

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The friction and wear of alumina and zirconia ceramics doped with various weight percentages (0.5% wt, 1% wt and 5% wt) of CuO was studied. Dry sliding tests by using a pin-on-disc tribotester were conducted on these materials against commercially available Al2O3, ZrO2, SiC, and Si3N4 ceramic balls.

The results show that CuO give a significant reduction of friction only when the alumina and zirconia doped with CuO were sliding against Al2O3 balls. The coefficient of friction of CuO doped in alumina sliding against Al2O3 balls reduces from 0.7 to 0.4 and hardly depends on the normal load and the velocity. On the other hand, CuO doped in zirconia can reduce the coefficient of friction (when sliding against Al2O3 balls) from 0.8 to a value of about 0.2 and 0.3 depending on the normal load.

SEM pictures taken from the wear track showed that smooth patchy layers were formed. These smooth patchy layers, which carry the normal load, are responsible in reducing the coefficient of friction.

*Keywords: Ceramics, CuO, low friction*

# Optimization of the Airbus A380 Vertical Tail Plane

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The design of large aircraft substructures considering local failure criteria such as buckling and local strain is a task that typically involves the optimization of a large number of components combined with the optimization of the structure as an assembly, similar to a multi-level optimization approach. The objective of the study the progress of which is presented is the development of a design tool that performs a weight minimization of a large aircraft substructure (the Vertical Tail Plane (VTP) of the A380) while considering a topological variety as well as the scaling parameters.

The first step of such a procedure involves the solution of a coarse global finite element (FE) model (of the entire substructure) under a global load case, the output of which is a local load set for all components. The optimization of all components is done using a Genetic Algorithm (GA) coupled to a Neural Network (NN) based response surface. The substructure is then reassembled based on the modified (optimized) components and new local loads are computed using the aforementioned global model. This process is repeated until convergence is achieved (local loads or optimal designs do not change anymore).

Results include the optimization of simple box under a twisting load case. Tests on the full VTP structure will commence shortly after submitting this abstract. The presentation will explain the basics of the developed optimization program and show results.

# Topology Optimization using a Topology Description Function approach

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## Introduction

The objective of topology optimization is to obtain a structural design that optimizes an objective function and satisfies the constraints, where beforehand nothing is known about the structure, except the loads and the supports, and the so-called reference domain, i.e. the space in which the design must be found. The common approach is to generate a mesh of elements on the reference domain, and then to determine which of the elements should contain material and which not. Consequently, the design of the structure and the discretization are heavily coupled. This has some drawbacks, and alternative approaches are desired where the geometry description is decoupled from the finite element discretization.

## Topology description function approach

The Topology Description Function (TDF) approach is such an approach: The TDF is written as a superposition of parametrized basis functions, and maps each point of the reference domain to a value. Then, the part of the reference domain for which the TDF exceeds a cut-off level is assigned material, and the rest is void. In this manner the geometry of a structure is determined by the parameters of the TDF.

A finite element (FE) program is used to evaluate the performance of the design, i.e. the objective value, constraint values and design sensitivities are determined.

## Optimization approaches

The application of the TDF approach changes the form of the optimization problem. Now the objective is to find the optimal values for the parameters of the TDF using the results of the FE for feedback. Several optimization approaches are applied, namely the genetic algorithm, evolutionary strategies and gradient-based methods. The results show that genetic algorithms are too expensive with respect to computational effort. Evolutionary strategies are very attractive, but lack a sound mathematical basis, which is required to construct strategies for less intuitive optimization objectives. Based on the preliminary results, it seems that gradientbased methods work for small test problems. For larger cases, more research is required.

# Finite element simulation of draping with non-crimp fabrics

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Liquid-resin-infused non-crimp fabric (NCF) based composites offer lower cost without a significant drop in in-plane performance compared to prepreg technology. However, processability and performance are conflicting aspects. Easily drapeable and easily infusible NCFs often result in poor mechanical performance and vice versa.

The objective of this study is to develop a design tool that models both the production and the performance of NCF based composites. This design tool will allow to find an optimum between processability and performance. For components exhibiting double curvature, the process of draping the NCF on the mould plays a key role. The fibre distribution after the draping dominates both the filling process and the mechanical performance of the finished part. A finite element (FE) model to simulate the draping process of NCFs on arbitrary geometries is under construction. The model must identify problem regions during the draping and it must determine the fibre distribution in the final NCF.

The first step in the development of the model is the identification of the different deformation mechanisms of a unit cell. The model description of these mechanisms is based on semi-empirical laws. The possibility of the individual fibres to slide through the stitches is an unconventional part of the deformation. The mechanical behaviour of the NCF is implemented into membrane elements of an FE package to simulate the draping process. The results of these simulations will be validated against dedicated experiments with non-uniform deformation.

# Gradient-enhanced response surface building

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Optimization and reliability methods often rely on a high number of computationally expensive function evaluations. In order to reduce the computational costs, the response surface method can be used to approximate these expensive evaluations by means of a simple (for example polynomial) function. However, if the number of design variables is large, the required number of expensive function evaluations also becomes very large.

In some cases gradient information is available, which means that both the value of the response function and the derivatives of the response function with respect to the design variables are available. Generally, gradient information is useful only if it can be calculated at low cost. For example, in case of finite element analysis, the semi-analytical approach can be used to calculate the gradient information at a fraction of the time of an original analysis.

If gradient information is available it could potentially be used for response surface building. This would result in a reduction of the number of expensive function evaluations and/or an accuracy improvement of the response surface. In an attempt to include gradient information into the response surface, weighted least squares methods have been used by several authors. The weights can be obtained using different weighting schemes or by means of iterative weighted least squares. Gradient information can also be included in the Kriging method, a popular approximation method in structural optimization.

In this presentation, several approaches to include gradient information in the response surface will be discussed.
First, a two-step approach will be presented. In this method separate response surfaces are constructed for function values and gradients, which are subsequently blended. Simple analytical one- and two-dimensional examples will be used to illustrate the approach. Secondly, it will be demonstrated that gradient-enhanced response surface building can be treated as a multi-objective problem. In this case, the objective functions are the errors in function values and gradients, which have to be minimized simultaneously. This method has been tested by means of several examples. The effect of the plan of experiments on the accuracy of the method has also been investigated.
Finally, a method will be presented that takes into account the typical length-scale in the response function. If a small length-scale is present, the gradients will provide local information. In that case a response surface may be constructed consisting of a global approximation augmented with radial basis functions. The gradient information can be used to construct the radial basis functions. This approach will be demonstrated by means of two examples. In the first example the 1-dimensional Griewank function is approximated. The second example deals with the Griewank function in eight dimensions. Both examples show that the accuracy of the approximations has been improved by using gradients. The examples also show that for problems in higher dimensions the number of required points becomes very large.

# Modelling of strain path change effects on the basis of dislocation structure evolution

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Most of the real industrial metal forming processes are characterised by a complex strain path history, which locally can be considered as a sequence of uniform deformations fast succeeding each other. Typical examples can be found in the packing industry (beverage cans subsequently being deep drawn, wall ironed and necked/flanged/shaped) and in the automotive industry (parts subsequently being stretched and deep drawn, or hydroformed and stretched). A change in strain path has a significant effect on the mechanical response of metals. Macroscopically the effect of a certain prestrain becomes manifest in an increased reloading yield stress, transient hardening, hardening recovery, and failure shift compared to a monotonic deformation of the virgin material. For a particular material the intensity of the effect is influenced by the amount of prestrain and the amplitude of the strain path change. The complexity and significance of the strain path change effect therefore require careful investigation of the physical origins of this effect in order to model the deformation behaviour adequately.

The hardening behaviour of metals physically originates from a complex microstructure evolution. This work deals with the contribution of the evolution of the dislocations cell structure to the mechanical response of metals under monotonic deformation and after a strain path change. Dislocation cells are formed by the statistical trapping of dislocations and are recognised as volume elements within which the dislocation density is well below the average density and which are separated from adjacent volume elements by more or less well-formed dislocation boundaries. The evolution of the cell structure appears as sharpening and shrinking under monotonic deformation. After a strain path change, however, the pre-existing dislocation structures tend to dissolve in the course of loading in the new direction and new structures with a size and orientation corresponding to the new level and direction of the strain are formed. These fluctuations in the structure evolution are commonly associated to transient hardening behaviour after a strain path change.

Material with developing cells is modeled here to behave like a composite consisting of a periodic array of two types of elements: the hard cell walls and the soft cell interiors. The cell walls and cell interiors are defined as areas with high and low dislocation density correspondingly. The heterogeneous distribution of dislocations in the cell structure causes heterogeneity of the plastic strain. In the cell interior component plastic glide is much easier then in the cell walls where slip is impeded by the high density of tangled dislocations. To ensure compatibility of plastic deformation across the interface between the hard and soft phases, polarized layers of geometrically necessary dislocations are introduced at the interface. These layers are also a source of long-range stresses in the material.

The validation of the model is performed by comparing the results with experimental data on the deformation behaviour of copper, which was subjected to a sequence of two uniaxial tensile tests performed in different directions. The model is capable of describing the material behaviour for monotonic deformation and for deformation with a strain path change. The predictions of the model on the strain path change effect, its dependency on the amount of prestrain and on the amplitude of the strain path change are in good agreement with the experimental data.

# Parameter Optimisation Techniques for Robot Identification and Realistic Dynamic Simulation

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Robotised laser welding is an application, which requires high tracking precision at high speed motions. For prediction of the weldability of a seam, a closed-loop dynamic simulation of the robot is essential. In order to accurately predict the path tracking errors of the robot along a laser welding seam, realistic dynamic robot models with accurate model parameters are crucial. An accurate model of an industrial robot must therefore include all significant dynamic properties, such as inertia and joint friction. Furthermore, the robot controller should be included in the model as well.

For the modelling of the manipulator arm, a non-linear finite element formulation [2] has been applied, in which links and joints are modelled by beam and hinge elements. The identification of the inertia properties is based on an inverse dynamic identification technique. For this purpose, the dynamic model is written in a so-called parameter linear form:

For the modelling of the manipulator arm, a non-linear finite element formulation [2] has been applied, in which links and joints are modelled by beam and hinge elements. The identification of the inertia properties is based on an inverse dynamic identification technique. For this purpose, the dynamic model is written in a so-called parameter linear form:

$$\underline{\tau} = \Phi(\ddot{\underline{q}}, \dot{\underline{q}}, \underline{q})\,\underline{p} \qquad (1)$$

where the joint torques $\underline{\tau}$ are expressed as a product of the regression matrix $\Phi(\ddot{\underline{q}}, \dot{\underline{q}}, \underline{q})$ and the inertia parameter vector $\underline{p}$. The regression matrix is a function of the joint position $\underline{q}$, velocity $\dot{\underline{q}}$ and acceleration $\ddot{\underline{q}}$. In an inertia identification experiment, the robot is moved along an excitation trajectory $\underline{q}(t)$, while the joint torques are recorded. Using a linear least squares optimisation, the unknown inertia parameters are found. For an optimal identifiability of the parameters, the trajectory is optimised for persistent excitation, while motion constraints are obeyed.

To prevent backlash, the bearings in the joints are highly prestressed. Unfortunately, this results in high joint friction torques, which are quite dominantly present in the total joint torque. Therefore, friction must be taken into account in the inertia identification in order to achieve accurate values for the inertias. The friction models can be identified independently from the inertias using dedicated experiments. For the modelling of the joint friction, the LuGre [1] model is used. It is adapted for non-linear viscous friction at high velocities.

The controllers of industrial robots are generally very closed. In order to model the controller, it has been reverse engineered by means of standard system identification tools. The controller model has been included in the complete closed-loop robot model within MATLAB/SIMULINK. In the presentation, the modelling, identification and simulation of an industrial robot (Stäubli RX90) will be demonstrated by comparing simulation results with measurements of a motion experiment.

**References**

[1] C. Canudas De Wit, P Olsson, K Astr¨om, and P. Lischinsky. A new model for control of systems with friction. IEEE Transactions on Automatic Control, 40(3):419–425, 1995.
[2] J.B. Jonker and J.P. Meijaard. SPACAR-computer program for dynamic analysis of flexible spatial mechanisms and manipulators. In W.Schiehlen, editor, Multibody Systems Handbook, pages 123–143, Berlin, Germany, 1990. Springer-Verlag.

# Optimal Spreading of Fiber Bundles for Thermoplastic Impregnation

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Thermoplastic composite materials exhibit higher impact properties and generally show a higher toughness compared to thermoset materials. Unfortunately, the high viscosity of thermoplastic polymers hampers manufacturing of thermoplastic composite products.
In the present research, a prototype impregnation device [1] for thermoplastic polymers delivers promising results in terms of fiber bundle impregnation and the application in the filament winding process. However, the current geometry of the impregnation device is based on good workmanship and did not arise from a thorough numerical study. This triggered the development of a mathematical model of the impregnation device.

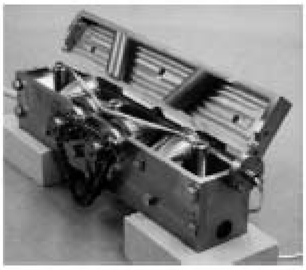

Figure 1: Prototype impregnation device (Length 40cm)

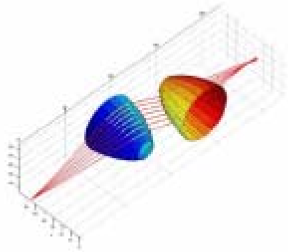

Figure 2: Visualization of a simulated fiber bundle over two rolls.

The model is able to simulate fiber bundles over rolls of arbitrary shape, see Figure 2. The fiber bundle is modeled by individual geodesic filament trajectories which all start in the same point. This point represents the inlet die of an impregnation device. Only those filament trajectories are considered which reach a fictitious exit plane at the end of the sequence of rolls. In this exit plane, an optimal location for the outlet die is determined for which the fiber bundle, spanned by the filaments, has its largest contact area with the rolls. The impregnation quality of the fiber bundle is judged by this contact area, where it is assumed that a higher contact area results in a higher degree of impregnation. The contact area incorporates both spreading and contact length of the fiber bundle.

The model described above is used in an optimization process with design variables as shape, location and number of rolls and location of the inlet die. The most optimal result will be used for the construction of an improved impregnation device.

## References

[1] Marissen, R., Drift, L. van der and Sterk, J., Technology for rapid impregnation of fibre bundles with a molten polymer, Composites Science and Technology, 60, pp. 2029-2034, 2000.
[2] Weustink, A.P.D. and Keulen, F. van, Optimal spreading of fiber bundles through an impregnation device with convex rolls, 18th Annual Technical Conference American Society for Composites, October 19-22, 2003, Gainesville, Florida, USA.

# 4

# SURVEY

## of

# POSTER PRESENTATIONS

This section contains a survey of poster presentations of actual PhD-projects within the Graduate School Engineering Mechanics. Individual poster presentations are collected in a separate report, which will be supplied at the start of the symposium and can be obtained from the Secretariat of the Graduate School. Furthermore, poster presentations are available through:

**http://www.em.tue.nl**

# Survey of Poster Presentations

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| Ir. C.A.J. Beijers | UT | Near-source sensor strategies for active isolation |
| M.Sc. E. Chtcherbakov | TU/e | Development of a Maxwell's Solver |
| Ir. D.B. Chung | TUD | Stochastic Finite Elements - Applied to Layered Materials |
| Ir. N.E.Conza | TUD | Dynamic model of the human pelvis - An experimental approach |
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| M.Sc. I. Hernandez- | UT | Fast Multilevel Techniques in Acoustics |
| Ir. C. van ‘t Hof | TUD | Mechanical Characterization of Curing Thermosets |
| Ir. R.A. Huls | UT | Coupled model of gas turbine vibrations |
| Ir. C. Iacono | TUD | Development of an inverse procedure for parameters estimate of numerical |
| M.Sc. J.H. Jacobs | TU/e | Framework for sequential approximate optimization |
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| M.Sc. Y. Kasyanyuk | TU/e | Mesoscopic modelling of faitgue damage and crack initiation in aluminium |
| Ir. M.P. Kruijer | UT | Modelling of a steel reinforced thermoplastic pipe |
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| Ir. R. Loendersloot | UT | Geometry and Permeability of Non-Crimp Fabrics |
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| Ir. J. Mediaville | TU/e | Ductile fracture: (dis)continuous and combined approaches |
| Dipl.-Ing. C. Michler | TUD | Subiteration - Preconditioned GMRES for Fluid-structure Interactions |
| Ir. N. Mihajlovic | TU/e | Friction-Induced Limit Cycling in an Experimental Drill-String Set-Up |
| M.Sc. P. Mohanty | TUD | Operational Modal Analysis in the presence of Harmonic Excitations |
| T. Pannachet | TUD | Performance of p-finite element method in a gradient-enhanced damage |
| M.Sc. A. Pavlov | TU/e | The tracking problem: from linear systems to nonlinear |
| Ir. G. Poort | TUD | Material Properties of Glenoid Cancellous Bone |
| Ir. J.J.C. Remmers | TUD | The coheive segments method |
| Ir. M.J. de Ruiter | TUD | Topology optimization: Topology Description Function and Response |
| Ir. H. Super | UT | Hybrid Isolation of Structure Borne Sound Reduction on Performance |
| M.Sc. Y.C. Tasan | UT | Measurement of Wear on Asperity Level Using Image Processing Techniques |
| M.Sc. B. Tasic | TU/e | Solving Flow of ODE with Discrete Velocity Field |
| Ir. R.H.W. ten Thije | UT | Finite element simulation of draping with non-crimp fabrics |
| M.Sc. P. Tiso | TUD | Reduction methods for non-linear static and dynamic Finite Element analysis |
| Ir. R.L.J.M. Ubachs | TU/e | Microstructural behaviour of solder joints |
| Ir. K. Vervenne | TUD | Gradient Enhanced Radial Basis Functions |
| Ir. B.H. Villa Rodriguez | UT | Braiding of RTM Preforms |
| Ir. R.R. Waiboer | UT | Robot Modelling, Identification and Simulation |
| Ir. A.P.D. Weustink | TUD | Optimal Spreading of Fiber Bundles |

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# 2

# POSTER PRESENTATIONS

This section contains poster presentations of actual PhD-projects within the Graduate School Engineering Mechanics. Aim of these presentations is to provide a general impression of the current research topics. Presentations are in alphabetic order on the (first) author. A survey of contributions is included at the next pages. Full color versions of the presentations are available through:

**http://www.em.tue.nl**

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