## A Summaries of EM-dissertations completed in 2001

In 2001 nineteen dissertations were completed within the context of the Research School Engineering Mechanics. This appendix contains summaries and further information on each of them. Included are:

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Fractional Evolution Equations in Banach Spaces.

Bajlekova, E.G.

Advisors: Prof.Dr.Ir. J. de Graaf, Prof.Dr. Ph.P.J.E. Clément.


EM research theme: Mechanics of Materials

In recent years a considerable interest has been shown in the so-called fractional calculus, which allows us to consider integration and differentiation of any order, not necessarily integer. To a large extent this is due to the applications of the fractional calculus to problems in different areas of physics and engineering.

The fractional calculus can be considered an old and yet novel topic. Starting from some speculations of Leibniz and Euler, followed by the works of other eminent mathematicians including Laplace, Fourier, Abel, Liouville and Riemann, it has undergone a rapid development especially during the past two decades. One of the emerging branches of this study is the theory of fractional evolution equations, i.e. evolution equations where the integer derivative with respect to time is replaced by a derivative of fractional order. The increasing interest in this class of equations is motivated both by their application to problems from viscoelasticity, heat conduction in materials with memory, electrodynamics with memory, and also because they can be employed to approach nonlinear conservation laws.

This thesis is concerned with abstract fractional evolution equations. It is an outcome of the author's research during her Ph.D. study at the Eindhoven University of Technology (December 1997 - September 2001). Most of the material in the thesis is based on the following articles from this period:


Chapter 1 contains notations and some background material. In Chapter 2 ([1],[2],[4]) applying functional analytical methods, the solvability of the problem and the properties of the solution operator are investigated. We develop a theory, which extends the classical theory of C_0-semigroups of operators. The subordination principle is studied in detail in Chapter 3 ([3]) applying transform methods. Chapter 4 ([5]) is devoted to the maximal L^2 regularity. In Chapter 5 the problem of regularity is tackled in Hilbert space settings by the method of sums of accretive operators. The obtained regularity results are applied in Chapter 6 ([6]) to investigate the nonautonomous fractional evolution equations, a transient case between linear and quasilinear problems. As an application, the global solvability of a quasilinear fractional evolution problem is obtained.
Noise Reduction by Viscothermal Acousto-Elastic Interaction in Double Wall Panels.

Basten, T.G.H.

Advisor: Prof.Dr.Ir. H. Tijdeman.

University of Twente, June 2001.
ISBN 90-365-1597-1

EM research theme: Structural Dynamics and Control

Noise and vibrations are an important problem in the modern society. Our society is becoming more and more crowded and we use all kinds of noise and vibrations producing appliances and means of transportation. Moreover, there is a trend towards lightweight design, which leads often to increased noise and vibration problems.

The present study focuses on the feasibility of noise reduction with double wall panels. The emphasis is put upon the application of the dissipative properties of a thin air layer between two flexible plates. Vibration energy is converted into heat by the viscosity and thermal conductivity of the air between the plates. The goal of this study is to develop and to validate efficient models including viscothermal wave propagation for double wall panels which make it possible to investigate the noise reduction for both airborne and structure borne noise at low frequencies.

Because of the strong interaction between the vibrations of the plates and the air layer it is essential to apply fully coupled acousto-elastic models. Apart from inertia and compressibility, the effects of viscosity and thermal conductivity are taken into account. For this purpose the so-called low reduced frequency model is very suitable.

As a first step, relatively simple two-dimensional models are derived which are solved analytically. The results demonstrate that especially structure borne noise can be reduced effectively with the dissipative properties of the air layer. The transmission loss for airborne noise is hardly affected by the viscothermal effects. These findings are consistent with results found in the literature.

Acousto-elastic interaction is investigated in depth by means of a numerical, analytical and experimental study. The emphasis is put upon the behaviour of coupled acousto-elastic modes. In the case of uncoupled domains one can speak of structural and acoustic modes. In the coupled case all modes are acousto-elastic. It depends on the energies in the structural or acoustic domain whether the modes can be denoted as structural dominated or acoustic dominated. The corresponding eigenfrequencies are followed as a function of the thickness of a rectangular plate covering a closed acoustic cavity. In some cases a continuous crossover takes place between structural and acoustic dominated modes. This happens when the uncoupled frequencies are not too far apart and when the uncoupled mode shapes are able to exchange energy. This phenomenon is called spatial matching. Other important characteristics of an acousto-elastic system are the added mass and stiffness effects of the acoustic domain on the dynamic behaviour of the plate.

For realistic problems it is in most cases impossible to obtain analytical solutions for the vibrational behaviour and sound radiation characteristics of double wall panels. So one has to resort to numerical techniques. Therefore a numerical model has been developed. For reasons of efficiency the model is uncoupled in an interior and an exterior domain. The vibrational behaviour of the double wall panel is analysed with a finite element model, which includes acousto-elastic interaction. The computation speed is highly increased by the introduction of a special modal superposition method. With the vibration patterns of the plates after solution of the internal problem, the radiated acoustic power is calculated (external problem). The radiated sound power is calculated efficiently by the application of a reduction method based on so-called radiation modes. The numerical tools are validated by means of analytical solutions and also with experiments.

A special experimental setup is designed and built to verify the prediction methods for the vibrational and acoustic behaviour. Moreover, the setup is used to demonstrate the damping capabilities of a narrow air layer in a double wall panel. Numerical and experimental results agree fairly well. The results of a parameter study show that for the optimum use of the viscothermal damping the air layer has to be as thin as possible, that both plates have to be non-identical and that the thinnest plate has to be excited. In these cases maximum pumping of air between the plates is achieved. The presented numerical tools and results can be profitable for future design studies.
The application of obstructions in the air layer offers an extra possibility to create damping. This is investigated by means of an experimental study. Besides viscothermal damping, the working principle is based on vortex shedding from the edges of the barriers. The latter damping mechanism increases linearly with the vibration amplitude and depends strongly on the shape and configuration of the obstructions.
Continuous fibre reinforced plastics are increasingly being used in a wide range of disciplines. Traditionally, composite materials were almost only used in aerospace engineering and for advanced sporting devices. This limited field of application was due to high material, design and manufacturing costs. However, during the last decade composite materials became more and more an interesting alternative for traditional materials in many other applications.

Use of continuous fibre reinforced composites will further increase, when designing such composite products could be simplified. The design process basically consists of two stages: conceptual design, which mostly relies on engineering knowledge and practice, and detailed design. Within the detailed design phase, structural optimization is an efficient design tool.

The context of this thesis is automated shape optimization of fabric reinforced thermoplastic products, manufactured by means of the rubber forming process. Such an optimization scheme requires a simulation of the production process in order to obtain local fibre orientations. It also demands for a material model that predicts the mechanical properties of the composite material as a function of the fibre orientation. Once the local mechanical properties are known a Finite Element (FE) analysis must be carried out to obtain the structural response of the product under consideration. Without availability of accurate design sensitivities, automated shape optimization will be very computational expensive. The goal of this research is to develop and implement design sensitivity analysis in the context of structural optimization of fabric reinforced products.

In a FE context, so-called Semi-Analytical (SA) design sensitivities are widely used because of their ease of implementation and computational efficiency. On the other hand, however, SA design sensitivities are widely known because of their accuracy problems. It was found that these accuracy problems become especially dominant in case of slender structures, where individual elements undergo relatively large rigid body motions. Therefore, a refined SA method has been developed, that is based on exact differentiation of rigid body modes at element level. The RSA formulation is superior to a SA formulation, as the results obtained are just as good or much better, while the additional costs for implementation and computing are minor. The RSA method has been successfully applied to linear, linearized buckling, geometrically nonlinear and limit point analyses. Moreover, it has also been applied to second order design sensitivity analysis. Although there are still some topics that might be interesting to study, the RSA method is expected to have reached its final form.

A method to simulate forming processes of woven fabric reinforced composites by applying optimization techniques is presented. The idea is to enhance a standard geometrical algorithm on the basis of optimization techniques. For this purpose, placement of the fabric is controlled by a set of unknowns that defines the position of a single warp and fill yarn on the mould surface. Once these two yams are positioned, the draping process is continued according to a standard geometrical approach and subsequently the value of objective and constraint functions for the current solution are determined. The unknowns are determined by using an optimization technique and proper objective and constraint functions that reflect the forming process at hand. The optimization based forming simulation method, was expected to be computational efficient and to provide accurate design sensitivities. However, calculation of design sensitivities turns out to be involved. As the optimization based forming simulation method appeared to be inconvenient, it is recommended to study use of FE methods to simulate deep drawing of fabric reinforced thermoplastic products. This could be advantageous since calculation of design sensitivities might be more easily and extension to fabrics consisting of several layers might be more efficient. Moreover, the same model can be used to carry out structural analysis.
Deformation as a Trigger for Pressure Sore Related Muscle Damage.

Bosboom, E.M.H.

Advisors: Prof. Dr. H. Kuipers, Prof. Dr. Ir. F.P.T. Baaijens
Co-advisors: Dr. C.V.C. Bouten, Dr. Ir. C.W.C. Oo

University of Maastricht, October 2001.
ISBN 90-386-2962-1

EM research theme: Mechanics of Materials

Pressure sores are localised areas of tissue breakdown in skin and/or underlying tissues such as the subcutaneous fat and muscle. They are primarily caused by prolonged mechanical loading applied at the interface between skin and supporting surfaces and can occur, for example, when patients are bedridden, wheelchair bound or wearing prostheses. Pressure sores are depressing for the patient and can be very painful, especially in the early stages. The prevalence of pressure sores is high; around 10% of all patients in acute care hospitals have pressure sores. An effective prevention of pressure sores is impeded by a lack of knowledge on the aetiology. It is not known how external loading at skin surface is transferred to local stresses and strains within the tissues and how these local loads eventually can result in tissue damage. Moreover, although prevention focuses on skin, muscle tissue is more susceptible to mechanical loading and the most severe pressure sores often initiate in muscle.

The aim of the present thesis is to obtain insight into the relationship between prolonged mechanical loading and localised muscle damage. A combined approach is chosen involving the development of both an animal model and a finite element model. The animal model aims at relating controlled external loading to the location and amount of muscle damage. The finite element model is developed to assess the local mechanical conditions within the muscle in response to external loading. Comparison of the local muscle damage with the local mechanical conditions within the tissue should then provide information on the local mechanical parameters critical for the onset of damage and enable a better prediction of the consequences of external loading for tissue damage.

Former animal models on the aetiology of pressure sores were limited to the question whether or not damage occurred. Hence, to relate controlled external loading to local muscle damage, a new rat model and damage analysis techniques were employed. The tibialis anterior muscle and overlying skin in the hind limbs of eleven male Brown Norway rats were compressed between an indentor and the tibia for a few hours. The muscle was excised 24 hours after loading and monitored for tissue damage as defined from loss of cross-striation of the muscle fibres and infiltration of mononuclear cells. A three dimensional reconstruction of the muscle and the induced damage was obtained and both the amount and the location of damage were quantified using a semi-automated image-processing program. If the loading protocol induced damage, the damage was localised to a zone near the place of indentation, running from superficial to deep muscle layers.

The above-mentioned histological damage analysis techniques have the disadvantage of being labour-intensive and thus limit the number of experiments. Moreover, histological techniques are destructive and therefore exclude follow-up and clinical studies. Hence, besides histology, T2-weighted high-resolution magnetic resonance imaging (MRI) was applied to evaluate the muscle tissue. Using the same experimental set-up to induce damage, in vivo MR images of both the loaded and contralateral hind limb were now obtained 24 hours after loading. Subsequently; the tibialis anterior muscles were processed for histological examination, which was applied to evaluate the MRI results. In the MR images signal intensity appeared higher in the loaded regions of the muscle as compared to the unloaded regions. The location of the region with higher signal intensity coincided with the location of damage assessed from histology. Moreover, the area of higher signal intensity in the MR image was in good agreement with the area of damage assessed from the histology. It was therefore concluded that MRI is a promising alternative for histological techniques in research on pressure sore aetiology.

To determine the local stresses and strains in the muscle during the loading, a finite element model has been developed of the tibialis anterior muscle and the surrounding tissues. The model makes use of constitutive equations to describe the passive behaviour of the muscle. Since no data were available for the passive transverse properties of skeletal muscle, compression experiments were performed to determine these properties. Special care was taken to maintain the viability of the muscle tissue during the experiments by preserving the neurovascular supply. The protocol led to an inhomogeneous stress-
and strain-distribution in the muscle. To assess these a plane stress model was employed, in which an incompressible viscoelastic Ogden model was used to describe the passive muscle behaviour. The material parameters were determined from fitting the modelling results on the experimental data (numerical-experimental method).

However, some modelling uncertainties remained, i.e. the isotropy in the material law for the passive muscle, the transverse properties for skin, the direction of load application and the boundary condition at the membrana interossea, a stiff collagenous membrane between tibia and fibula. To determine the effect of the choices made for these model parameters, extra simulations were performed. From these parameter variations, it was concluded that the majority of the above-mentioned choices hardly affected the results (< 8%). However, changing the boundary condition at the interface between muscle and membrana interossea had a major effect. In future studies, the deformation at this boundary should thus be determined, e.g. by applying MRI-tagging.

By comparison between the animal model and the finite element model, the hypothesis was investigated that the onset of pressure sore related muscle damage is triggered by prolonged cell deformation. If a direct relationship exists between cell deformation and muscle damage, the maximum shear strain distributions in the tissue determined by the finite element model must coincide with the amount and location of initial muscle damage assessed in the animal experiments. Although the calculated shear strain distributions showed some overlap with the area of muscle damage, the current results were not convincing enough to conclude that cell deformation is the major trigger for muscle damage. Further research should elucidate the relative role of cell deformation and other causal factors for tissue breakdown (i.e. ischaemia, interstitial changes) in the onset of pressure sore related muscle damage.

The comparison between the animal experiments and the finite element calculations was complicated by the large variation in susceptibility for muscle damage found for the different rats. In clinical observations, differences in susceptibility of patients are explained from different underlying pathologies or differences in additional risk factors, like age, mobility and nutritional state. However, these rationales cannot be applied here as animal characteristics, experimental and loading conditions were strictly controlled. This finding needs further study as the amount of tested animals was limited and only one loading protocol was applied. However, if differences in susceptibility cannot be explained by underlying pathologies or known risk factors, this may have large consequences for pressure sores prevention.

The present thesis demonstrated that deformation can result in considerable muscle damage, but the underlying pathways leading to muscle breakdown still remained unclear. The combined approach, involving both experimental and numerical studies, is however a solid means of obtaining a clear understanding of the aetiology of pressure sores.
Design of a Multi-Process Multi-Product Wafer Fab.

Campen, E.J.J. van

Advisors: Prof.Dr.Ir. J.E. Rooda and Prof.Dr. E.H.L. Aarts
Co-advisor: Dr.Ir. L.F.P. Etman

ISBN 90-386-2752-1

EM research theme: Structural Dynamics and Control

Semiconductor wafer fabrication is one of the most complex manufacturing processes. The complexity is brought about by the high-tech processes being applied, their constant development, the multitude of process steps, and their reoccurring nature. Hence, comprehensive control strategies are required. Nowadays, due to this complexity, building a wafer fab costs over one billion dollars, whereas operating costs run into hundreds of millions of dollars a year. As designing has a great influence on costs and expenditures, a good fab design provides the manufacturer an advantage over his competitors.

The product of a wafer fab is a finished wafer, containing hundreds to thousands of integrated circuits (ICS) on its surface. Semiconductor industry distinguishes manufacturers of high-volume production of ICS, such as microprocessors and memories, and low-volume production of customer specific ICs, also called multi-process multiproduct (MP2) wafer fabs. High-volume ICs are generally made to stock, whereas MP2 fabs usually are made in small batches on customer orders. Contrary to high volume manufacturers, who are merely interested in maximizing productivity, MP2 manufacturers also aim for reliable and short cycle times. The contradiction of running a fab economically, thus at high productivity, and achieving reliable and low cycle times simultaneously is the challenge in designing wafer fabs.

Although a lot of research has been done on specific elements concerning the design of wafer fabs, like layout optimization or scheduling performance, no systematic approach is known that describes the activities and tools needed to design an MP2 wafer fab. The objective of this thesis is twofold. First to structure the design process of an MP2 wafer fab and to describe the accompanying methods and tools needed during the design process. Second to apply the proposed approach to the design of Philips' Mos4you wafer fab in Nijmegen.

Designing an MP2 wafer fab is structured into four design activities: determination of objectives and constraints, design of the architecture, design of capacity and layout, and design of the operations. Each successive activity is an extension of the previous one, as it reveals another level of detail. After determining the objectives and constraints, the architecture of both the material flow as well as the control system are determined. Design of the architecture is essential to achieve a well-balanced design of the wafer fab. Next, the resources and their location are determined. Finally, during the design of the operations the detailed micro layout, operating procedures, and control policies are determined. Continuous improvement activities are part of the design of operations.

Following are the relevant design choices that have been implemented in Mos4you. Objectives, constraints, and characteristics of the fab led to a hybrid functional architecture. The layout of the fab is divided into main processing areas, each containing a specific process technology, for example, metal deposition, lithography, etc. Each sub-process area or bay is equipped with the appropriate process equipment and optimized for its purpose. A partially automated material handling and storage system is applied to obtain controllable and cost effective wafer transport and storage, while flexibility is guaranteed. The production control concept consists of a lot release strategy and a lot sequencing strategy. Lots are to be released at the desired productivity level, however, the amount of work-in-progress triggers exception handling. Once on the shop floor, lots are processed according to a specific sequence of recipes and lots are dispatched for process steps in an order aiming for maximum flow line balance. Improvement studies were carried out, considering specific areas in isolation. During these studies detailed analysis was performed, taking many sources of variability into consideration which resulted in improved floor layouts, improved working procedures and refined sequencing rules.
Optimization of Thin-Walled Packaging.

Dijk, R. van
Advisor: Prof. Dr. Ir. A. van Keulen

Delft University of Technology, October 2001.
ISBN 90-9015084-6

EM research theme: Structural Mechanics

The present thesis describes the physical (solubility and permeability), the mechanical (structural behavior) and the chemical (oxidation) processes, which are very often relevant to a thin-walled package. Initially a study has been carried out which identified the relevant requirements for the involved package, here being a plastic bottle for edible oil. These requirements are based on experimental work and consist of empty and filled compression testing and vacuum resistance testing. Subsequently, these experiments have been modeled with Finite Element Analysis (FEA). The latter required several special numerical adaptations for the deformation induced internal pressure and solubility effects which play a significant role during vertical compression of filled bottles.

Each of the processes as mentioned above have been examined by many researchers, however a model which combines structural behavior, permeability and solubility effects and oxidation of the contents can hardly be found in literature. If it is desired to optimize a complete structure then it is however necessary to take all these processes into account. In the present thesis such a model is described, moreover the model is general applicable and can be used to determine the behavior of the package and to a certain extent the behavior of the contents as a function of time. The mechanical behavior of the package required for this can be determined in a quasi-static way with the help of FEA. The amount of dissolved gas is determined using Henry's law. The gas pressures determine the influence of the permeability effect, while the oxygen gas pressure and an initial oxidation speed determine the oxidation. Accurate oxidation data is however scarce. If such accurate data is required one could set up experiments for this, if not approximate data may be used. An explicit integration scheme has been used to determine the behavior of the package as a function of time.

Applying this model to the round bottle indicated that permeability effects could be neglected in the present setting. Moreover, it has been indicated that the mechanical behavior of the structure can be simplified to a piece-wise linear volume pressure relation. This simplification originates from the fact that all initial present oxygen reacts in a relatively short period of time with the contents. Hereafter the behavior of the structure is fully determined by the nitrogen pressure. Since time dependent behavior of the package has not been taken into account, the situation after disappearing of all oxygen is investigated as a static problem. The piece-wise linear behavior of the involved structure can easily be identified with a linear FE analysis and a buckling FE analysis. The latter has been exploited during optimization of the involved structure.

During analysis of the optimization problem, sensitivity analysis has been used to identify the most important design variables of the structure. Hereafter, an optimal design was looked for, making use of the Multipoint-Approximation Method (MAM). For the present bottle the optimization led to a bottle where weight savings up to 46% can be achieved. The origin of these weight savings comes however not directly from the optimization analysis itself. Most potential weight savings have been 'created' during the definition of the constraints. In common practice the constraints are mostly based on history or experience while in this thesis the constraints are derived from buckling requirements.
Modern Strategies for the Numerical Modelling of the Cyclic and Transient Behaviour of Soils.

Heeres, O.M.

Advisor: Prof.Dr.Ir. R. de Borst

Delft University of Technology, December 2001.
ISBN 90-407-2261-7

EM research theme: Computational Mechanics

This Thesis discusses advanced material models, which can be applied to simulate static, cyclic, as well as time-dependent behavior of soils (Chapters 3 and 4). A uniform numerical framework is formulated to integrate these models along the loading path (Chapter 5). Finally, it is investigated whether the method of enhanced assumed strains can be used to enrich constant strain triangular elements such that the deformation generated by dilatant/contractant plasticity models can be described (Chapter 6).

Material modeling

Chapter 2 describes some aspects, which characterize the behavior of soils. Successively, attention is paid to the dilatant nature of soils caused by the granular microstructure, the influence of the density on the behavior of the material, the evolution of the irreversible deformation during loading and unloading, and on the time-dependent behavior. Then, stress invariants and strain invariants are introduced, the isotropic elastic relations are reviewed, and the finite-element formulation is introduced.

Chapter 3 first gives the basics of standard elastoplasticity. Subsequently, the following elastoplastic models are discussed: subloading plasticity and generalized plasticity. Compared to standard elastoplasticity these models more realistically simulate the behavior of soils, since a smooth relation is used to describe the transition from elastic to plastic behavior, they predict a continuous stress-strain response. Moreover, during unloading and reloading irreversible straining can be simulated.

Next, hypoplasticity is introduced. The structure of this model is fundamentally different from the structure of elastoplasticity. Firstly, in hypoplasticity the strain rate is not additively split into a reversible and an irreversible part. Secondly, the evolution of the stress is not governed by quantities, which always can be geometrically interpreted like yield functions, flow rules or potential functions, but by a nonlinear algebraic expression, which relates the total strain rate to the stress rate.

In Chapter 4, Perzyna viscoplasticity and Consistency viscoplasticity are presented and compared. In spite of the different formulations, it appears that their constitutive parameters can be uniquely related. For the Consistency model, an expression is derived for the viscoplastic multiplier, by integrating the rate-dependent consistency requirement. Accordingly, for both models the evolution of the viscoplastic strains can be expressed in an equivalent manner. Subsequently, the subloading model is extended with a time-dependent term, which precisely reflects the overstress in a Perzyna model, and the resulting rate-dependent subloading model is specified for clay.

Numerical approach

Chapter 5 provides a numerical framework in which elastoplastic, hypoplastic and viscoplastic material descriptions can be integrated along the loading path. In here, the equations which govern the evolution of the stress, the internal variables, the inelastic deformation, and the nonlinear elastic parameters, are discretized and casted in a residual format. The algorithm has been elaborated for the constitutive models presented in Chapters 3 and 4, and numerical examples are provided. To find the solution of the equations, the Newton-Raphson iterative scheme is applied. The algorithm performs well, also if complex stress paths are followed. Finally, subincrementation techniques can be smoothly incorporated into the algorithm.

Finite element formulation

Chapter 6 introduces the locking problem, which can take place if triangular lower order finite elements are applied in combination with a dilatant/contractant plasticity model. It is explored whether enhanced assumed strains can be used to enrich these elements, such that the deformations emanating from the material model, the boundary conditions and the loading can be represented. This chapter demonstrates that the patch test together with the characteristic area-interpolation cause that locking of constant strain triangles cannot be remedied using enhanced assumed strains.
Non-Linear Vibrations of Anisotropic Cylindrical Shells.

Jansen, E.L.

Advisor: Prof. Dr. J. Arbocz

Delft University of Technology, December 2001.
ISBN 90-5623-075-1

EM research theme: Structural Dynamics and Control

This thesis presents a theoretical investigation of the vibration and dynamic stability behaviour of thin-walled anisotropic cylindrical shells. The main emphasis is placed on the vibration behaviour when the vibration amplitude is of the order of the wall thickness of the shell, generally referred to as the large amplitude flexural vibrations or nonlinear flexural vibrations. The research focuses on several characteristic aspects of the nonlinear vibration behaviour, namely the coupling between asymmetric and axisymmetric modes and the possibility of circumferentially travelling waves. The influence of important parameters, such as geometric imperfections, static loading and boundary conditions, receives particular attention. In the present approach, semi-analytical (i.e. analytical/numerical) models with different levels of complexity are developed. In a Level-1 Analysis (or Simplified Analysis) a small number of assumed modes which approximately satisfy "simply supported" boundary conditions at the shell edges, are used in a Galerkin procedure or variational method. In a Level-2 Analysis (or Extended Analysis) the specified boundary conditions are accurately satisfied by means of the numerical solution of corresponding two-point boundary value problems. Nonlinear Donnell-type governing equations are adopted in combination with classical lamination theory. It is assumed that axial compression, radial pressure, and torsion statically load the cylindrical shell.

The main conclusions of the research can be summarized as follows. Several models have been developed to simulate the nonlinear vibration behaviour of cylindrical shells. These models are in accordance with a strategy for the analysis of complicated shell problems. The models can simulate the characteristics of the behaviour and are capable of capturing the effects of the relevant parameters indicated earlier. An adequate modelling of the secondary coordinates is essential. The results of the models developed are qualitatively in agreement with available experimental results.

The thesis can be divided into three main themes. First, the stationary nonlinear flexural vibrations of imperfect anisotropic cylindrical shells under harmonic radial excitation are studied via a Level-1 Analysis. The assumed deflection function includes two asymmetric modes. The driven mode is excited directly by the applied harmonic radial pressure. The companion mode is in shape identical to the driven mode, but circumferentially ninety degrees out-of-phase. The axisymmetric mode satisfying a relevant coupling condition with the asymmetric modes is included in the assumed deflection function. The static state response is assumed to be affine to the given two-mode imperfection, which consists of an axisymmetric and an asymmetric mode. A possible skewwedness of the asymmetric modes is taken into account.

Approximate solutions for the dynamic state equations are obtained by applying Galerkin's method and the method of averaging in sequence. Frequency-amplitude curves for free and forced nonlinear vibrations are obtained from the resulting set of nonlinear algebraic equations in the averaged vibration amplitudes. Due to an internal parametric resonance, for a large excitation in the spectral neighbourhood of the linear natural frequency a coupled mode response can occur. This response may be interpreted as a travelling wave pattern in the circumferential direction of the shell. Results of the nonlinear vibration analysis of a specific anisotropic cylindrical shell are presented. The effect of imperfections and axial loading on the vibrations of this anisotropic cylinder is discussed.

The second part of this thesis is also within the framework of a Level-1 Analysis. The transient nonlinear flexural vibrations and several dynamic stability problems of imperfect anisotropic cylindrical shells, namely dynamic buckling and nonlinear parametric excitation, are analysed via numerical time-integration. The in-plane inertia of both the fundamental axial and the fundamental torsional mode, including the inertia effect of a ring or disk at the loaded end of the shell, is taken into account approximately. Viscous modal damping is included in the analysis. Hamilton's principle is applied as an approximate solution method in order to obtain a set of ordinary differential equations in the coefficients of the assumed deflection modes. The dynamic response is obtained via numerical time-integration of the resulting differential equations. The coupled mode nonlinear vibration behaviour of an isotropic shell is...
simulated using this approach. Nonstationary vibrations where the response drifts between single mode and different types of coupled mode solutions are observed in a small frequency region near resonance. In addition, characteristic results for dynamic buckling and nonlinear parametric excitation are discussed for several specific isotropic and anisotropic cylindrical shells.

Finally, in the third part of this thesis, the effect of the boundary conditions at the shell edges on the flexural vibration behaviour of anisotropic cylindrical shells is assessed via a Level-2 Analysis. The effect of finite amplitudes is investigated via a perturbation expansion for both the frequency parameter and the dependent variables. Imperfections and a nonlinear static deformation are included in the formulation. The perturbation procedure eliminates the time dependence and leads to sets of boundary value problems with the spatial coordinates as independent variables. A Fourier decomposition in the circumferential direction of the shell is used in order to eliminate the dependence of the solution on the circumferential coordinate. Hereby the partial differential equations are reduced to ordinary differential equations. The elastic boundary conditions are satisfied accurately by solving the resulting two-point boundary value problems numerically via the parallel shooting method. Numerical results show the effects of different sets of boundary conditions on the nonlinear vibration behaviour of several specific isotropic and anisotropic cylindrical shells. The results of the Level-2 analysis are compared with results of Level-1 analyses and results from the literature.
This thesis covers numerical tools for low noise design of MRI scanners, as used in clinical practice. In combination with the previously published thesis of Kuijpers (1999), it describes the results of a project entitled "Acoustic modelling and design of MRI scanners", that was funded by the Dutch Technology Foundation (STW). The MRI scanner is a typical example of a device that, due to its underlying operational principles, generates excessive noise as a side effect. If the current operational principles are unchanged, sound level reductions of 40 dB or more are desirable compared to the scanners of today.

Such reductions require the combination of a number of extensive actions. Firstly, these actions concern the noise from the gradient coil that escapes through the tunnel in which the patient is located. Also of importance, is the sound that originates from noise and vibration in the gradient coil, and that is transferred to the magnet housing. Another noise source is the inductive excitation of the magnet housing by the gradient coil. The technical realisation of such extensive actions, however, is restricted because of limitations in space, applicable materials and maximum allowable vibrational displacements of the gradient coil.

The goal of the aforementioned STW-project is the development of design tools for the optimisation of gradient coils, in order to develop low noise scanners. The software based on the Finite Element Method and on the Boundary Element Method, that was available at the start of the project, was not suitable for this purpose. The required frequency range of a few kHz already leads to excessive analysis times for every single design alternative. This prevented the application of such software as a tool for design and optimisation. In the thesis of Kuijpers (1999), a method is developed for the efficient calculation of gradient coil noise radiation. By taking advantage of axisymmetry and by using a special formulation of the radiation operator, an enormous CPU time reduction is obtained.

The goal of this thesis is the development of a much more extensive numerical tool. The previously developed acoustical module is integrated into this tool. The newly developed additions apply to the mechanical excitation, to the coil vibrations, and to the optimisation of coil structures.

The Lorentz forces, that excite the coil, are described in terms of a spatial Fourier series. From this description, symmetry conditions of the excitation are derived. Next, an efficient numerical method for the analysis of the coil vibrations is implemented, which exploits the global axisymmetry and the symmetry of the excitation. Existing techniques are improved, which has led to shorter CPU times and to a wider range of applicability. Also, research has been conducted into the modelling of frequency dependent fibre reinforced materials and structures with glue layers. Now, quick estimates of the effects of design changes on the noise levels can be made with the help of these numerical models. Geometry, material behaviour, mechanical excitation and kinematic boundary conditions can be parameterised at will. This is demonstrated using a number of such parameter studies, including an investigation into the effects of Lorentz force balancing. Therefore, by applying the developed tools, the possibilities for noise reduction within a certain design space can be explored. Such information facilitates wellfounded decisions about actions that are needed to achieve a certain reduction.

Parameter studies in this thesis show that the acoustical behaviour of certain structures can change considerably after the application of small design changes. Most optimisation methods, however, are not effective when the system responses fluctuate rapidly. For that reason, research is conducted into a method that does work under such circumstances. This has resulted in the adaptation and implementation of a mid-range method, which is further enhanced by coupling it to a strategy in which multiple goals can be optimised simultaneously. The end result is an optimisation tool that better agrees with the needs that emerge from engineering practice. The method is also fit for use in applications other than low noise design.
The axisymmetric models constructed in this thesis are tested restrictedly by measuring an MRI scanner in operation. Using a laser-Doppler vibrometer, the velocity distribution on part of the inner surface of a gradient coil is sampled. The measurement setup is designed such that the strong sound fields and magnetic fields have negligible influence on measurement accuracy. One of the goals of the measurements is to learn more about the vibrational behaviour of the gradient coil.

Measurement results indicate that the coil does not behave like an axisymmetric structure. Partly for that reason, responses calculated using axisymmetric models deviate from the measured response. Also, the measurements reveal behaviour that is typical for devices with a high degree of structural complexity. Therefore, it is likely that the many details that are lacking from the axisymmetric models give rise to the discrepancies between calculated and measured responses. Modelling all these details, however, would require too much time, both for modelling and for the actual analyses. It is advised, therefore, to direct future research towards the development of efficient numerical tools in which details can be smeared out in the form of local uncertainties. Nonetheless, there is also a degree of similarity between calculated and measured responses. Therefore, the idealised models that are used in this thesis produce a number of useful design hints.

In closing, it can be stated that, in their present form, the developed tools can already be employed in evaluating the feasibility of new design concepts. Also, they are sufficiently efficient and versatile to quickly become familiar with the structural-acoustic behaviour of coil models that already contain more details. The developed tools are directly applicable for the low noise design of homogeneous or layered axisymmetric structures, other than MRI scanners. A relevant example is the optimisation of axisymmetric enclosures.
Thermally Induced Wear Transition in Ceramics.

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University of Twente, June 2001.
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EM research theme: Mechanics of Materials

Technical ceramics are promising materials for specialized applications. These materials have a lower density than steels, yet they combine high compressive strength and hardness with chemical stability. These properties are maintained at elevated temperatures. Unfortunately ceramics are quite brittle, a property that easily gives rise to material loss when ceramics in contact are moving relative to each other. Therefore designers tend to stick to traditional materials for fear of excessive wear of ceramic components.

In a recent past, much research has already been done into the wear of ceramics. This research will be reviewed in this thesis. From this research it appears that often transitions occur between legions of different wear types. Particularly the transitions between a mild wear regime, where operation of components can be considered safe, and regions of severe wear, where loss of material as well as generation of debris might lead to problems, are of interest. In this thesis a model to predict such a transition has been developed. This model is valid for a wide range of material combinations as well as a wide range of operational conditions. In this model the stresses that are caused by the frictional heating are causing the failure of the ceramic components in concentrated contacts. It is assumed that when these stresses exceed a certain, material-dependent, threshold, fracture of the material will occur. This fracture will lead to a severe wear type. In order to calculate under what conditions this will happen, an effective heat conductivity has been defined. In this effective heat conductivity conduction as well as heat removal by movement of the contacting surfaces are considered. The effective heat conductivity depends on the velocities of the surfaces and their thermomechanical properties. Besides this, the velocities, normal force and coefficient of friction are used to calculate the amount of generated heat. With this, a dimensionless contact number is defined. For a certain contact situation, the value of this number, relative to a threshold value, determines whether wear will be mild or severe. Subsequently, this model has been validated using pin-on-disc tests. These are performed on two different machines to increase the possible range of operational conditions. The results of these experiments show good agreement with the model, where the threshold value of the contact number is very close to the predicted value. This means that it is now possible to predict accurately the operating limits of a design, using ceramic materials.
Numerical Analysis of Viscous Flow Using Composite Grids, with Application to Glass Furnaces.

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EM research theme: Computational Mechanics

The glass for glassware that surrounds us in our daily life is produced in glass melting furnaces. The raw materials (soda, sand) are put inside the furnace at one end, then they are heated by gas burners and melt gradually, thus forming a glass flow. Studying the glass flow is essential for understanding melting and mixing processes. Some phenomena in the furnace occur locally but nevertheless affect the global pattern of the flow. We consider bubbling -a process used to enforce a natural convection in the melt, and stirring -a process intended to prevent untimely solidification of the melt. The flow model consists of equations for an incompressible viscous fluid, equations of state and boundary conditions imposed by the geometry of the furnace. The model is too complex to be solved by analytical methods; therefore we need to use numerical methods.

The resolution of the local phenomena in the flow by conventional methods have undesirable effects: the refinement based on non-uniform tensor-product grids leads to excessive memory and computation time usage, the refinement based on a single discretisation on a composite grid leads to a very complex data structure. These difficulties can be avoided by using a technique called Local Defect Correction (LDC). LDC is an iterative procedure that combines the results on a coarse global grid (covering the global domain) and fine local grid (covering the high activity areas).

Since LDC is not a solution method by itself we first build up a general solution algorithm for 3D viscous flow problems. To that end we consider a pressure correction algorithm in conjunction with a collocated grid. Pressure correction methods are iterative methods aiming at solving viscous flow problems (Navier-Stokes or Stokes equations). For each iteration of the pressure correction algorithm one needs to solve a linear system for the pressure. The system is singular, which reflects the fact that the pressure is included in the flow equation via the gradient only. In practice the -system for the pressure turns out to be inconsistent in most cases. We suggest a procedure for mending this inconsistency. The procedure is based on the explicit formulation of the consistency condition, which depends on the boundary conditions for the velocity only. By correcting the latter we manage to satisfy the consistency condition.

The solution method is then used in LDC iterations. We consider two applications of the LDC iterations for the flow problems. In the first one both the problem on the global grid and the subproblem on the local grid are formulated in cartesian coordinates. The second application of LDC combines the solutions of the problems in the two different coordinates systems: cartesian and cylindrical. The fast convergence of LDC is demonstrated by a series of examples. A novelty in LDC for flow problems is a correction of the boundary conditions for the problem on a local grid. These boundary conditions are obtained by means of interpolation from the solution on a global grid. Without correction they give rise to inconsistent systems of equations. We suggest a correction procedure based on a discrete global mass balance. As we show, the correction introduces an error comparable with the interpolation error.

These LDC approaches are applied to two specific high activity problems, namely bubbling and stirring. For the bubbling we use a variant of LDC with global and local grids formulated in cartesian coordinates. For this type of LDC iterations we derive a complexity estimate in terms of the number of grid points used. Comparing the complexity of LDC to the complexity of the refinement by non-uniform tensor-product grids we show that LDC is much more efficient. The numerical experiments support this. The stirring is solved by LDC combining a cartesian global grid and a cylindrical local grid. A posteriori error estimates show second order accuracy of the LDC solution. For both examples we observe a fast convergence of LDC iterations.
Stokes Flow in Thin Films.

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EM research theme: Computational Mechanics

To describe the flow of a lubricant between two nearly contacting surfaces, in for example bearings, frequently use is made of the Reynolds equation. This equation is deduced from the Navier-Stokes equations under the assumptions that the gap between the surfaces and the Reynolds number is small. It has been used for the past one hundred years to analyze all kinds of hydro/aerodynamic lubrication problems. In most cases, it can accurately predict the characteristics of the flow in the lubricant film. However, with decreasing film thickness in bearings, the roughness of the contacting surfaces becomes more important and the Reynolds equation less appropriate. In this work it is studied under which conditions the Reynolds equation no longer approximates the flow accurately. To do so the assumption that the ratio film thickness to contact length is small is dropped. The flow can then be described by the Stokes equations. It is studied how the geometry of the contacting surfaces influences the difference between the Stokes solution and the Reynolds solution for the flow between two surfaces with on one surface a sinusoidal feature. Because generally there is no analytic solution to the problem, first a numerical algorithm was developed to solve the Stokes equations. This algorithm was subsequently used to quantify the difference between the Stokes solution and the Reynolds solution for different configurations of the contacting surfaces.

Not only the geometry of the surfaces can result in a less accurate Reynolds solution, relative to the Stokes solution, but also compressibility and piezo-viscous effects have an impact on the accuracy of the Reynolds solution relative to the Stokes solution. This subject is also studied. A clear example of a compressible lubricant is gas (air). Also for gas lubrication problems the Reynolds equation is normally used. In this work the flow under a step geometry is studied to investigate the validity of the Reynolds equation for this case. Another example of a pressure dependent density can be found in the simulation of cavitation. In order to obtain a realistic model for the lubricant flow in a narrow gap, a cavitation algorithm should be incorporated. It prevents the pressure from dropping below the vapor pressure. In this work a two-phase model is implemented in the numerical algorithm to solve the Stokes equations.

Finally, the influence of a pressure dependent viscosity on the validity of the Reynolds equation is studied for the flow in a channel containing a sinusoidal surface feature. The thesis is concluded with conclusions and with some recommendations for future research.
Computational Modelling of Failure in Fibre Reinforced Plastic.

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ISBN 90-9014375-0

EM research theme: Mechanics of Materials

Fibre reinforced laminated plastics are becoming increasingly popular as structural materials. The material combines a light weight with a high performance and is therefore ideal for application in e.g. racing bicycles and aeroplanes. Especially in the last industry weight reduction at maintained or even increased strength compared to conventional materials is an important money saving fact. The lower the weight of the aeroplane itself, the higher the freight or passenger carrying capacity or the flight range. However, the high costs of the material and the maintenance are still a major drawback. Maintenance periods are small, since damage often cannot be detected with the naked eye, while it does decrease the load bearing capacity enormously. To increase the time span between maintenance sessions, damage prediction methods have to be developed.

In this thesis a number of material models is discussed capable of describing two of the three major failure mechanisms of fibre reinforced laminated graphite-epoxies with long unidirectional fibres in the individual plies, namely delamination and transverse matrix cracking. The third failure mechanism, fibre breaking, mainly occurs after the other two and is thus of less importance for the utilisation demands of a structure.

The delamination can be divided into two groups, namely pure model delamination as it occurs in the mid-plane of a symmetric laminate and mixed-mode delamination. For both types material models have been developed, which have been implemented in a finite element code and then applied to the analyses of uniaxially loaded graphite-epoxy laminated composites. For model delamination the material model is based on the formalism of orthotropic damage mechanics. Mixed-mode delamination models are based on either plasticity or damage mechanics to study the effect of both principles on the analysis time and robustness.

Driven by the comparison of plasticity and damage mechanics, the transverse matrix cracking model is again based on the formalism of orthotropic damage mechanics. With this model uniaxially loaded strips containing a centre hole are analysed.

The models are verified by comparison of the analyses results with experimental results found in literature and numerical results of other authors.
Coordinated Control of The Zero Inertia Powertrain.

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EM research theme: Structural Dynamics and Control

Powertrains for passenger cars have been receiving substantial improvements throughout the last few years. Successful efforts have been undertaken to improve the fuel economy by adapting the engine-, aerodynamical and tire design. Reduction of vehicle mass seems to have the highest potential but is hardly realizable in practice if at all. This is merely caused by the increased safety and comfort standards. The desire of society for a healthy and clean environment, preferably for a low price, encouraged car manufacturers to launch new and innovative solutions for better fuel economy and lower emissions. Mostly these innovations are forced though also financially supported by governments.

Since about ten years it is fully understood that improved fuel economy can also be realized by the transmission in the powertrain. Not only higher transmission efficiency but more importantly the way the engine and transmission jointly cooperate to increase the engine’s combustion efficiency is the key to a substantial fuel economy improvement. The capabilities in this area can be intensified by utilizing a continuously variable transmission (CVT). A CVT can transmit the engine torque and change its speed continuously. Besides this advantage above other transmission (manuals, stepped automatic) it possesses a relatively high overdrive ratio with low penalties on volume.

For example, the CVT’s overdrive can lower the engine speed to about 1500 rpm at 80 km/h, whereas standard transmissions manipulate at least 1900 to 2200 rpm at this vehicle speed. The former can be shown to gain about 10 to 15% fuel economy advantage. However, a disadvantage of the high overdrive is the lack of vehicle responsiveness (driveability) when pushing the accelerator pedal. Mostly because of safety reasons this kind of operation is socially unaccepted and solutions are mandatory to break the paradox between driveability and fuel economy.

In the framework of the EcoDrive project at the Technische Universiteit Eindhoven a technical innovation is elaborated that indeed banishes the mentioned paradox. Besides the work described in this thesis two other theses are written on this subject: 'Component Control for the Zero Inertia Powertrain' by Bas Vroemen en 'Transmission Design of the Zero Inertia Powertrain' by Roell van Druten.

The innovation originates from the idea to exploit the inertia of a flywheel beneficially for realizing an initial and persistent response at request. Connecting a planetary gear stage with the flywheel in parallel to the CVT, it is possible to decelerate the flywheel while accelerating the engine with the CVT (for example to facilitate a take-over manoeuvre). The torque stemming from the flywheel is directly transmitted to the wheels until the moment where the engine can deliver the requested power sustainably on its own. In this thesis an unique state of the powertrain is identified where the total torque stemming from the engine sided inertias are compensated exactly by that of the flywheel. This state is termed ‘zero inertia’ hence the denomination Zero Inertia Powertrain.

A proper coordination of engine torque and shift speed of the CVT ratio during and after the engine transitions is extremely important. By carefully choosing the setpoints for the engine’s electronic air throttle and for the hydraulically controlled CVT, the driveability and fuel economy can be optimized at all times. This is termed coordinated powertrain control and together with demonstrating the improved fuel economy and driveability form the main subject of this thesis. Models are required to gain increased insights in the ZI powertrain. Moreover, for the coordinated control design and for validation dynamic models are mandatory. In part II of this thesis modeling, control and testing of the ZI and CVT powertrains are described.

In conjunction with Bas Vroemen and Roell van Druten part I is written showing that improved fuel economy pays a price in terms of research capacity, resources, weight and volume. In Part I it is made plausible that the ZI powertrain forms a mediating solution amongst these actors.
On the Cohesive Surface Methodology for Fracture of Brittle Heterogeneous Solids.

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EM research theme: Mechanics of Materials

The numerical simulation of the final stage of deformation, i.e., fracture of the material, has posed enormous conceptual and numerical problems during the past decades. The traditional description of the deformation of materials in terms of stresses and strains was initially extended into the failure regime by supplementing the constitutive law with a softening branch. Numerical simulations with the finite element method dealing with the fracture behavior of materials and using such traditional constitutive models showed that the localization of deformation occurred inside a single row of elements. Upon mesh refinement, the fracture energy dissipation occurred in an ever smaller volume of material, rendering the total energy dissipation zero. The source of this problem has been identified as the loss of ellipticity of the governing equilibrium equations. Besides the issue of zero energy dissipation, the numerical simulations showed a dependence on the mesh alignment. This hampered an objective simulation of fracture paths.

As a solution to this problem, two different paths were followed. The first path follows the traditional description of material deformation in terms of stresses and strains and supplements the constitutive description with non-local or gradient terms. Such enhanced constitutive models have a regularizing effect on the equilibrium equations, i.e., in numerical simulations loss of ellipticity of the governing equations is prevented and as a result objective simulations of the fracture path and energy dissipation can be made. However, fracture is described in a smeared sense and true loss of displacement continuity cannot be attained.

The second path follows a different approach and discards the idea of describing the fracture behavior in terms of stresses and strains. Instead, fracture is described in a discrete manner. Cracks and crack-like features are described by displacement jumps and energetically conjugated tractions. The transition between the state before fracture, in which displacement continuity exists, and the state after fracture, in which the crack flanges are traction-free, is described through a softening relation between the surface traction and the mutual separation between the crack flanges. These approaches include, for example, embedding displacement discontinuities in the finite element formulation through the use of incompatible modes in the strain field. Another approach is to add extra shape functions to the finite element description, which describe the effect of a crack like feature.

The cohesive surface methodology falls in the second category. It describes fracture of a material in terms of a traction-separation relation between two surfaces. Although, oftenly, the traction-separation relation has been phrased in a rate-independent manner, rigidly relating the traction as a function of the separation, the cohesive surface methodology allows for a much more flexible approach. Various physical processes can determine the traction that bridges the future crack flanges. Once properly identified, such physical processes can be incorporated in a traction-separation law. The traction then evolves as a function of various fracture processes and is not fixed a priori. This approach is used in this thesis, in which cohesive surface constitutive models are motivated by micromechanical considerations. Once a cohesive surface model is formulated, detailed numerical simulations with the finite element method are performed. The cohesive surfaces and the bulk material are discretized separately, each having their own constitutive model. In this thesis, the bulk material is assumed to remain elastic, although more general non-linear constitutive models pose no extra conceptual difficulties. All energy dissipation is assumed to originate from the generation of cracks. In numerical simulations regarding fracture, the crack path is often fixed a priori. However, the cohesive surface methodology is not restricted to this. In this thesis, cohesive surfaces are used in between all finite elements to allow for the largest freedom of crack path selection. To this end, constant strain triangular elements are used along with linear cohesive surfaces. Fracture now evolves as a result of the mutual interaction between continuum deformation and (possibly multiple) fracture.

Two constitutive models for cohesive surfaces have been developed motivated by micromechanical considerations. The first constitutive model describes crazing in amorphous polymers. A craze is a crack-
like feature in which the crack flanges are still bridged by a network of polymer fibrils, which give the craze some load-bearing capacity. Combined experimental and analytical work has led to criteria relating stress state components to the initiation of a craze nucleus. Since no general craze initiation criterion is available and the cohesive surface methodology is flexible enough to allow for any craze initiation criterion, we have used a specific criterion valid for the amorphous polymer PMMA. The stage of initiation of a craze nucleus is followed by the widening of the craze. Experimental work has indicated that during this stage, fibrillar material locks due to the intense stretching of the material causing new, amorphous material from the bulk-craze interface to be drawn into the craze. This process is called surface drawing. Based on these experiments and other detailed numerical analysis, a rate-dependent widening law is proposed governing the cohesive traction in this stage. Finally, the craze fibrillar material will break down. The kinematic description of this stage is still far from complete and a rather crude scheme is employed. This constitutive model for a craze is used in a detailed analysis of crazing in front of an initially sharp crack. It is shown that, when certain precautions in the discretization are taken, the cohesive surface methodology can predict the correct fracture path if the crack path is not specified a priori.

The second cohesive surface model deals with the description of the failure of cementitious composites. From experiments it is known that cementitious composites are heterogeneous from the macroscale down to the microscale. Due to this, the description of fracture of this kind of materials has been particularly difficult. It is proposed that upon loading of a cementitious composite, due to the heterogeneity, the material is damaged already for very low stress levels. Microcracks grow on a sub-micron level, generating small cracks on a higher level of observation. Neglecting the complexity of the material structure, this process is highly simplified in a damage formulation for the cohesive surfaces. However, the evolution of the damage variable is specified to be a function of the current level of damage and the stress state. Once proper values for the material parameters are chosen, this results in a rate-dependent cohesive surface model applicable to the fracture of a cementitious composite on a mesolevel. On this level of observation, the cementitious composite is modeled as a three-phase material, consisting of a cement matrix and aggregates separated by the interfacial transition zone. It is shown that the model captures the experimentally observed phenomenon of crack face bridging and describes the rate dependence of concrete deformation upon change of loading rate qualitatively correct.

Although the cohesive surface methodology results in a finite energy dissipation for crack growth upon mesh refinement due to the specification of the traction as a function of a displacement jump, the second problem in crack growth simulations is not solved, i.e., there still exists a mesh alignment sensitivity. If the discretization exhibits a clear alignment, crack growth will either progress along that direction or crack growth simulation is not possible at all. A solution to this problem is obviously to make sure that the discretization does not have a preferential orientation. Two other precautions must be taken during crack growth simulation with the cohesive surface methodology. The first is that the elastic stiffness of the cohesive surfaces must be large enough to ensure that the elastic opening of the cohesive surfaces remains limited. The second precaution follows immediately from this restriction and applies to the solution algorithm employed. It is shown that the high elastic stiffness of the cohesive surfaces results in a high conditioning number of the system of equations. For explicit time integration schemes, often used for dynamic calculations, this results in high frequency oscillations upon the opening mode of the cohesive surfaces. Therefore, path dependent cohesive surface models cannot be used in such a context. One must then either employ the assumption of quasi-static deformations or, in case the influence of inertia is essential for the problem at hand, use an implicit time integration scheme with artificial numerical damping in the high frequency deformation modes.
On the Friction of Thin Film Rigid Disks

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University of Twente, May 2001.
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EM research theme: Structural Dynamics and Control

This thesis describes the investigation into the friction between a head and a rigid disk (the so-called head-disk interface) of rigid disk drives.

Rigid disk drives are used to store and retrieve vast amounts of data. These drives consist of a stack of rigid disks on a common rotating spindle. Each disk surface has a head that can move across the disk for recording and reproducing data. The head is connected to a spring suspension, which presses the head against the disk surface with a light normal load. During normal operation of the drive, each head is separated from its disk by means of aerodynamic lubrication: As a result of the shape of the head and the relative velocity between the head and the disk, a thin pressurised film of air is generated at the head-disk interface. Due to the load carrying capacity of this film, the head flies above its disk surface. During powering on or off of a drive, the relative velocity is too low to create a sufficient load carrying pressure in each air film, and sliding takes place. During sliding the friction between head and disks is substantially larger than during flying. During the transition from sliding to flying the friction reduces. This change in friction makes that certain lubrication regimes (boundary, mixed, and aerodynamic lubrication) at the head-disk interface can be distinguished. The friction can be presented in a so-called generalised Stribeck curve, which gives the coefficient of friction as a function of a lubrication number.

In the rapid developing information technology, there is a continuous demand for disk drives with higher storage capacities. In order to further increase the capacity, the heads should be in virtual contact with the rigid disks whereby friction and wear have to be kept as low as possible. As a result of this, controlling the friction and wear becomes more and more important in rigid disk drives.

The investigation in this thesis has been carried out in order to come to a better understanding of the different lubrication regimes of a head-disk interface, such that the regimes can be predicted as a function of the operational parameters of the interface. The thesis provides an introduction into the problems of head-disk interfaces, an analysis of the head-disk interface, the development and analysis of a friction model, a dynamical analysis of the instrument that has been used for friction experiments, and, finally, the results of those experiments.

The friction model describes the friction force as a function of a lubrication number of the head-disk interface. The model is based on the following assumptions: the surface of the head is nominally flat, and rough, with a large number of asperities; the rigid disk consists of strong bonded thin films on a substrate and its surface is covered with a thin liquid lubricant layer; the surface of the rigid disk is considered smooth and flat; furthermore, a stiction force can occur between the rough surface and the liquid lubricant layer. The friction force has three components: a component determined by the microcontacts between the solid surfaces of the head and the disk, a component due to the shearing of the thin liquid lubricant layer, and a component determined by the gaseous lubricant film.

The model predicts that the generalised Stribeck curve shifts toward the left and that the stiction force at the head-disk interface decreases with increasing nominal pressure. The model predicts also a rather high stiction force in the liquid lubricant layer, especially when the thickness of the layer is in the order of the surface roughness of the head-disk interface and the applied normal load is low. The stiction force decreases with decreasing nominal area of contact. It also follows from the model that the normal load, in combination with the dimensions of the head, should be carefully chosen, not only for the purpose of aerodynamic lubrication, but also to minimise the friction in the boundary and mixed lubrication regimes. The elasticity of the solid surfaces of a head-disk interface is mainly determined by the elastic modulus of the substrate, the undercoat and the head. However, these moduli do not have a very significant influence on the generalised Stribeck curve.

Before the results of the friction experiments are discussed, a description and a dynamic analysis are given of the instrument that is used for these experiments. From the analysis the forces and displacements at the instrument are estimated. After describing the friction experiments, the experimental...
results are compared with the results obtained from the friction model. It follows that the friction model predicts qualitatively the shape of the experimentally derived generalised Strubeck curves. The generalised Strubeck curve shifts toward the left with higher applied normal load. The friction model also predicts this shift. In the boundary lubrication regime, the coefficient of friction at low loads is higher than that of an unlubricated disk. The take-off velocity increases slightly with the surface roughness of the head-disk interface.

From the results in this thesis, it can be concluded that rigid disk drives should be designed such that the head-disk interfaces are operating at the transition from mixed to aerodynamic lubrication. At this transition the friction force is minimal and the separation is low. Adjusting the nominal pressure or the relative velocity of the head-disk interfaces can do this. Adjusting the dimensions of the head can modify the nominal pressure.
Nonlinear Dynamics of Elementary Rotor Systems with Compliant Plain Journal Bearings

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EM research theme: Computational Mechanics

In many practical situations, so-called compliant journal bearings, that is, journal bearings with a relatively elastic bearing liner are used. An example of a compliant journal bearing is the water-lubricated rubber-lined journal bearing that is used to support the propeller shaft in ships. Because of the fact that journal bearings are nonlinear elements, they can have a significant influence on the dynamics of a rotor-bearing system. However, the dynamics of large rotor-bearing systems are generally studied using linear models, where the journal bearings are linearized about an equilibrium position. For a better insight in the dynamics of a nonlinear rotor-bearing system, a nonlinear dynamic analysis needs to be carried out.

In this thesis, compliant short and long plain journal-bearing models for rotordynamic applications are developed. These models consist of spatially discretized nonlinear partial differential equations, which are in fact large systems of nonlinear ordinary differential equations. Because of the dimension of these systems, the standard methods to calculate vibrations of nonlinear dynamic systems are too inefficient. Therefore, also an efficient numerical method to calculate vibrations of partial differential equations is developed.

The nonlinear dynamics of a rotor-bearing system with a rigid rotor in two compliant journal bearings are studied for different values of the relative bearing-liner compliance, using both the short and the long bearing models. It turns out that increasing the relative bearing-liner compliance decreases the stability threshold of a balanced rotor in compliant short journal bearings, while it increases the stability threshold of the same rotor in compliant long journal bearings. For an unbalanced rotor in compliant short journal bearings, the relative bearing-liner compliance has a significant influence on the rotor speeds at which the branch of synchronous vibrations changes stability and on the shape of the branch of sub synchronous vibrations. For the same rotor in compliant long journal bearings, increasing the relative bearing-liner compliance causes an increase in the rotor speed, at which the branch of synchronous vibrations becomes unstable. It appears that in contrast to rigid journal-bearing models the minimum film thickness of the compliant journal-bearing models can become zero and even negative. In other words, the compliant journal-bearing models predict the possibility of contact between the journal and the bearing. Because contact is not included in the models, physically impossible vibrations with negative film thickness can be found. For rigid journal-bearing models, contact cannot occur at all because of the fact that either an infinitely large load or an infinitely long time would be needed.

During experiments on a rotor-bearing system with a flexible shaft in a water-lubricated rubber-lined journal bearing, a nonlinear phenomenon is observed. The branch of synchronous vibrations contains two so-called cyclic folds, at which the branch changes its direction. If the rotor speed is varied past one of these cyclic folds, the system jumps to a remote part of the branch of synchronous vibrations. This phenomenon is probably caused by the nonlinear elasticity of the rubber bearing liner of the water-lubricated rubber-lined journal bearing.
The fuel economy of passenger cars can be improved in various ways. One can think of reducing the external load, for instance by lowering the weight and air drag of the vehicle. Another possibility is to improve the propulsion system, i.e., the powertrain. Increasing the efficiency of the different powertrain components, such as the engine and the transmission, is one way to do so. Another approach is to operate the powertrain as a whole in a more fuel-optimal way. Especially the operating point in which the engine delivers the required energy is of vital importance to the fuel consumption. While the efficiency of the modern combustion engine is thought to be close to what can be achieved, the field of alternative powertrain operation is by no means fully cultivated.

In the EcoDrive project underlying this thesis it was therefore chosen to concentrate on technologies in this field as means to save fuel. Based on a survey of fuel saving methods related to alternative powertrain operation, two of these methods were selected due to their high fuel saving potential relative to the additional weight, cost and complexity as compared to a conventional vehicle. The first of these methods, called E-line tracking, can save fuel by delivering requested stationary wheel powers in fuel-optimal engine operating points. The second method, called Stop-Go, improves the fuel economy by eliminating the idle fuel consumption of the engine at vehicle standstill. The actual difficulty in both approaches is to achieve the fuel savings without impairing the vehicle response to the accelerator pedal, also known as driveability. The project target was therefore set at saving 25% fuel with respect to a 4-speed automatic transmission on the NEOC driving cycle, without compromising the driveability.

For that purpose, a flywheel is connected in parallel to the transmission via a planetary gear stage. In case of E-line tracking, the flywheel operates as a power assist source during transients when the vehicle is to be accelerated starting from a fuel efficient, hence low engine speed. Because the resulting vehicle response appears as if the engine inertia is absent, the resulting powertrain is referred to as the Zero Inertia (ZI) powertrain. For Stop-Go, the flywheel can also be used to launch the vehicle from standstill. In the proposed design, called ZI Stop-Go, the vehicle and the engine can be accelerated simultaneously, enabling a Stop-Go functionality without a noticeable delay between pedal depression and vehicle launch.

The smooth exchange of energy between the flywheel and the rest of the powertrain during transient operation is possible through the use of a Continuously Variable Transmission (CVT). Furthermore, the CVT enables exact matching of the fuel-optimal engine operating points to the vehicle speed. This thesis is concerned with the development of the (pushbelt) CVT controller, and of the models required for that. The presented models are also useful for gaining insight into the operation of the CVT and for explaining empirical observations, such as power loss in the transmission. Special consideration is given to dealing with constraints like actuator and system saturation. The CVT controller is evaluated experimentally on a test rig and in a test vehicle, in conjunction with the setpoint generator derived in [Serrarens, 2001]. In stationary situations, the CVT controller achieves a close to maximal transmission efficiency without slip of the pushbelt, while highly dynamic transients are performed with acceptable tracking errors.

The second part of this thesis elaborates on the ZI Stop-Go powertrain. Several existing Stop-Go solutions are presented, and the potentials and operational difficulties of this technology are shown. The proposed ZI Stop-Go concept requires the introduction of two extra clutches. This solution is mechanically simple, but nevertheless complex to operate. It places heavy demands on its controls, both on the supervisory level and on the component control level. For that purpose, (hybrid) models of the powertrain are derived for developing a (hybrid) controller. The controller is evaluated using a more elaborate version of the mentioned model. Simulations of a kickdown vehicle launch show a response, which is comparable to that of a conventional CVT vehicle. The ZI Stop-Go transmission was realized and the CVT hydraulics were modified to enable the actuation of the clutches, also during engine shutdown. This transmission was mounted on the test rig and first tests yield promising results.
The contributions of the research covered in this thesis helped to largely achieve the project target, *i.e.*, a fuel saving of 18% was realized, while the driveability was even improved.
Discontinuous Modelling of Strain Localisation and Failure.

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The computational simulation of failure in solids poses many challenges. A proper understanding of how structures respond under loading, both before and past the peak load, is important for safe and economical constructions. This requires numerical models for failure, which are both faithful to the physical reality and mathematically well founded. A serious computational issue is that of objectivity with respect to the spatial discretisation of a problem. This requires that upon refinement of the spatial discretisation of a problem, a unique, physically meaningful result is approached. One approach to ensure objectivity with respect to spatial discretisation when simulating failure in solids is to allow displacement discontinuities in the solution. In this work, different techniques, of varying complexity, are developed to simulate displacement discontinuities, which are independent of the spatial discretisation using finite elements. The different techniques are then critically evaluated.

The first model examined involves adding only the effect of a displacement discontinuity to a finite element as an incompatible strain mode. This allows a traction-separation relationship to be applied at an interface and can be implemented simply in a standard finite element code. It is however shown that this type of model can be cast in an equivalent continuum format, a form that is known to be sensitive to the spatial discretisation. The second approach developed involves the addition of the Heaviside function to the underlying finite element interpolation basis. This method is based on the partition of unity concept, and allows the Heaviside function to be added locally to a finite element mesh to simulate a propagating displacement discontinuity. The approach is formulated for geometrically linear, geometrically nonlinear, quasi-static and dynamic problems. It is shown to be completely independent of the spatial discretisation. The partition of unity-based model is used also to simulate failure using a regularised strain softening model. When a critical level of inelastic deformation is reached, a displacement discontinuity is inserted. This model is better suited to modelling the entire failure process than a continuum or discontinuous model alone. Through numerical examples, it is shown that the inclusion of a displacement discontinuity during the failure process can lead to a different failure mode than for a continuum-only model.