Introduction: Microsystem design

Microsystem design is a large-scale engineering problem since it typically involves (Fig. 1):

- multiple components and/or
- multiple physics

Traditionally, the subsystem designs are sequenced in an “over-the-wall” fashion with limited feedback (Fig. 2a). An optimal system can only be obtained when the interactions between the subsystems are addressed more systematically: A coordination approach to system optimization is required (Fig. 2b).

Coordination approach

The developed coordination approach [1] has a number of benefits:

- design subproblems remain autonomous
- freedom to select local design/analysis tools
- flexibility in setting up coordination
- mathematical rigor of coordination

Each subsystem is represented by an optimization problem (Fig. 3). Interaction between subsystems is coordinated using an augmented Lagrangian penalty on shared variables and system-wide functions.

Case: Micro-accelerometer design

An ADXL150-type lateral capacitive accelerometer design problem (Fig. 4) is developed and will be used as a demonstrator case for the coordination approach. The developed models are analytical and therefore reproducible and suitable to test the new coordination method.

Outlook

As a next step, we desire to further develop the case study such that it may be used as a benchmark problem in multidisciplinary design optimization.

References

The HYDRA control study
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Introduction
At the European Space Research and Technology Center (ESTEC), the large HYDRA multi-axis vibration test facility is situated. With this facility, it is possible to perform dynamic testing of launcher payloads. In specific, the facility performs base driven tests of satellites to check if they can withstand launch conditions. HYDRA is superior to conventional installations because it is able to test heavy payloads (up to 20 tons) in a wide frequency range (1 to 100 Hz) and it can test them in any direction without changing the test setup [2]. The facility has been successfully used in the Envisat, Herschel and ATV testing campaigns.

Problem statement
Testing of large payloads on HYDRA does involve significant challenges. Because hydraulic cylinders are used to excite the payload base, eigenfrequencies attributed to the oil column stiffness are present in the frequency range of testing. When a flexible payload is tested on HYDRA, interaction between the payload structural dynamics and test facility dynamics come into existence. These phenomena can cause difficulties when satellites must be qualified for launch, resulting in additionally required simulations [1].

Research project
In 2007, the HYDRA control study was initiated by ESTEC in partnership with Delft University of Technology (TU Delft). The objective of the study is to analyze potential upgrades of the control algorithms of HYDRA in order to improve the dynamics, fully utilize its 6 DOF capabilities and extend the benefits of the HYDRA facility to its customers.

Plan of action
In order to achieve the study goals, the following analysis steps have been defined:

- analysis of the present HYDRA facility,
- literature study on control strategies of other shaker facilities,
- research into new and innovative control strategies for large shaker facilities,

The applicability of potential control strategies are investigated with the HYDRA Simulink® simulator [1].

References
Automatic partitioning and multirate applied to IC transient analysis

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Multirate transient simulation
The design of Integrated Circuits requires the time-integration of the following (large set of) differential-algebraic equations:

\[ \frac{d}{dt} [q(t, \mathbf{x})] + j(t, \mathbf{x}) = 0, \quad \mathbf{x} \in \mathbb{R}^d, \]  

(1)

where the unknown state vector \( \mathbf{x} \) consists of voltages and currents. Often, electrical circuits consist of parts with completely different activity levels. For that case multirate schemes have been developed.

![Figure 1: Example of multirate behaviour.](image)

We use a multirate version of the Backward Difference Formula (BDF) scheme which first computes \( q_A \) and \( j_A \) on a coarse grid. Afterwards the fast equation \( q_L \) is integrated at the fine time-grid. Finally the solution at the coarse time-grid is corrected by the refinement results. In [3] we showed that this method is absolutely stable if both parts are stable and weakly coupled. The local error can be controlled by adaptive timestepping of the coarse and fine timesteps [2]. The method has been applied successfully to several circuit models of NXP Semiconductors.

Automatic partitioning
The speed-up factor of a multirate method with coarse/refined stepsize \( H/h, m = H/h > 1 \) and workload ratio \( E < 1 \) satisfies

\[ S \approx \frac{W_{\text{sing}}}{W_{\text{mult}}} \approx \frac{1}{m + E}. \]  

(4)

The multirate factor \( m \) and the workload ratio \( E \) typically depend on the used partition. If \( \hat{e} \) is the estimated local error vector and \( p \) is the order of the used BDF scheme, then \( m \) can be estimated by

\[ \hat{m} = \left( \frac{\| \hat{e}_A \|}{\| \hat{e}_L \|} \right)^{1/p} \]  

(5)

The workload ratio \( E \) can be approximated by

\[ \hat{E} = \left( \frac{d_A}{d} \right)^\alpha, \]  

(6)

where \( \alpha \in (1, 3) \) and \( d = d_A + d_L \). Thus the optimal partition satisfies:

\[ \max_{\text{ind}_A, \text{ind}_L} S \approx \max_{\text{ind}_A, \text{ind}_L} \frac{1}{m + \hat{E}}. \]  

(7)

We developed several algorithms which are able to solve this optimization problem [1]. An extended version is also able to update the partition during the time-integration such that \( \hat{S} \) stays sufficiently large.

References

Multi-scale modelling of fracture in piezoelectric ceramics

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Introduction
Piezoelectric ceramics exhibit relatively large deformations through application of electric fields and vice versa. This electromechanical coupling makes piezoelectrics suitable for many applications, such as MEMS (micro electromechanical systems). The brittleness of piezoelectric ceramics makes the material, however, sensitive to damage. A hierarchical multiscale method [1] is developed to obtain an accurate and robust numerical model for assessing this damage.

Figure 1 : A hierarchic multi-scale method. Left: Partition of unity finite element model. Right: Polycrystalline micro models in the interfaces.

Implemented models
- On the macro-scale the partition of unity method (PUM) is used to model crack propagation. Discrete displacement and potential jumps caused by cracks can be modelled appropriately by enriching the continuous finite element shape functions with discontinuous Heaviside functions. The cohesive behaviour is obtained from the homogenised response of a microscopic finite element model.
- On the micro-scale a polycrystal is considered. Interface elements are inserted in the grain boundaries to model intergranular fracture, which is assumed to be the dominant fracture mode in the case of relatively small (a few microns) grains. An electromechanical cohesive law is obtained by complementing a mechanical law with electrical relations derived for a parallel plate capacitor.

Micro-Macro coupling
In a hierarchic multi-scale approach it is of crucial importance that the scales are coupled correctly. This is done by requiring that:
- The macroscopic jumps correspond to volume averages of the microscopic displacement and potential fields.
- The traction and surface charge density are defined such that the coupling neither removes, nor adds energy to the system.

Numerical results
Numerical experiments have been performed to test the developed method. The three-point bending test with off-centered crack (Figure 2) demonstrates the appropriateness of the method. A jump in the electric potential upon crack opening is observed, which is in accordance with experimental observations.

Figure 2 : Electric potential field for the three-point bending test with off-centered crack, loaded by a mechanical force and an electric voltage.

Microscopic imperfections can, especially in the case of MEMS, significantly influence the response of a system. Determination of the most important imperfections and their influence on the reliability of MEMS is the primary goal of this project.

Bibliography
A new engineering approach to predict the long-term hydrostatic strength of uPVC pipes

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Introduction

Extruded unplasticized Poly(Vinyl Chloride) (uPVC) pipes are certified for use in e.g. water distribution systems using pressurised pipe tests. During these tests the pipes are subjected to a certain temperature and internal pressure. At the same time the time-to-failure, the time at which the internal pressure drops due to rupture or fracture, is measured. These tests are time consuming and are therefore costly. To reduce both the costs and the required testing time, a model-based approach is proposed which can predict the time-to-failure of pressurized pipes based on only one (short term) test.

Initiation of failure

Although uPVC pipes can fail in a ductile, a semi-ductile or a brittle manner (Fig. 1), it is our hypothesis that plastic deformation initiates failure for all three failure modes. Upon loading a polymer, plastic deformation will accumulate continuously. At a certain (plastic) strain the polymer enters its softening region and fails due to localization of strain. Observations of our experimental data shows that, for uPVC, this critical strain ($\bar{\gamma}_{cr}$) is constant for a wide range of applied stresses and temperatures.

Model

From our hypothesis follows that the time-to-failure of a polymer under static load and isothermal conditions can be calculated with:

$$t_f = \frac{\bar{\gamma}_{cr}}{\dot{\gamma}(T, p, \tau)}.$$  (1)

The equivalent plastic deformation rate ($\dot{\gamma}$) resulting from the applied load and temperature can be equated with a pressure modified Eyring relation. The values for the material parameters in this model can be obtained by uniaxial tensile and creep testing. In addition a reference point or e.g. a tensile test is needed to determine the thermodynamic state of the polymer.

The model predictions agree quantitatively with data from Niklas et al. [2]. Both the slope and temperature dependence are predicted accurately for all failure modes. This supports the hypothesis that plastic deformation up to a critical level of strain, initiated failure for all three failure modes within the range of stresses and temperatures studied here. This makes the presented approach a promising tool for reducing certification costs significantly.

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Cryogenics

Cryogenics is the science of producing and studying low-temperature conditions. It comes from the Greek word Cryos, meaning “cold” and the shortened English verb “to generate”. It applies to temperatures from approximately -100°C down to absolute zero (-273°C = 0K)

In the 19th century the development of air-cycle refrigerators to preserve food evolved into the liquefaction of permanent gases by scientists. The last element to be liquefied was Helium at a boiling point of 4.2 K. The mechanical properties of many materials change dramatically when cooled to 100 K or lower. For example plastics and rubber become brittle and metals lose their electrical resistance (superconductivity).

Applications

New technologies in cryogenic applications like superconductors as well as practical applications such as transportation, astronomy (see fig.1), metallurgy and medicine lead to a growing interest in research for tribological properties at low temperatures.

These conditions of ultrahigh vacuum (<10^-7 mbar) and cryogenic temperatures result in some unique tribological problems. At low temperatures liquid lubricants will freeze or become too viscous. Furthermore, protective oxide layers formed under ambient conditions will not be restored.

Experiments

In order to measure material properties and friction in a cryogenic environment a friction tester is developed which makes it possible to measure friction forces, hardness and adhesion in vacuum at temperatures down to 60 K.

Figure 2: Cryogenic-vacuum tribotester

Model

The existing friction models describing the role of adhesion, deformation and shear of interfacial layer will be extended to include the influence of low temperatures and vacuum.

References

Introduction
An attractive way to perform vibration measurements is to measure the sound near the structure surface. However, the acoustical pressure is often overshadowed by background noise. Theory suggests that the fluid velocity does not have this drawback. We present new measurement results to confirm this claim.

Theory

(a) (b)

Figure 1: Acoustical response to (a) structural vibration and (b) incoming noise

In a 1D model, the pressure and velocity respond equally to structural vibration (see figure 1(a)). An interference pattern occurs for incoming noise because the sound reflects from the structure (see figure 1(b)). Near the structure surface, the pressure is at a maximum but the velocity tends to zero. By superimposing signal and ambient noise, it becomes clear that ambient noise hardly contributes to the velocity measurements near the structure surface: only structural vibration is measured.

Experiments

Figure 2: aluminium box, incoming noise source and sensor

Experiments are performed in an anechoic chamber. Structural vibration is created by a loudspeaker in a stiff aluminium box covered with a 1mm plate (see figure 2) and the incoming noise is represented by a loudspeaker in the far field of the structure. Pressure and fluid velocity are measured at several distances from the structure. Results are depicted in figure 3.

Conclusion
Both the structural behavior and the distance to the structure surface have significant impact on the sensitivity to background noise but off-resonance, velocity measurements tend to be 10dB less sensitive to noise than pressure measurements near the structure surface.

Figure 3: Experimental results. Left: Pressure, Right: fluid velocity
Multi-level Optimization of Composite Materials

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Introduction
Multi-level design optimization techniques rely on a decomposition of the optimization problem into separate levels or subsystems. These techniques incorporate design variables, objectives and constraints originating from different levels into the design.

Objective
The project concentrates on the development of a multi-level optimization framework for composite structures. Here both the non-linear mechanical behaviour as well as the optimization covers multiple levels.

Decomposition
Fig. 1 shows how a structure consists of a composition of smaller subsystems. Two different patterns may be distinguished: hierarchic and non-hierarchic.

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Coordination
The information that is necessary for the optimization of the decoupled subsystems needs to be coordinated in such a way that the entire system converges to a solution. One such approach is to add optimum sensitivity information to account for changes in lower levels due to changes in higher level subsystems. However, many other techniques are available depending on the decomposition used and pattern identified in the problem matrix.

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Discussion
We have identified a number of steps which allow a designer to choose a decomposition approach and a coordination strategy depending on the design problem or user preference. Furthermore, we have classified a number of mainstream multi-level optimization approaches recorded in literature.

Acknowledgement
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Strain Path Dependency in BCC Crystals
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Introduction
Materials experience a complex deformation history during sheet metal forming processes, which usually is characterized by a non-uniform strain path.

Objective
Changes in the strain path directions result in transient hardening and softening of the materials. The aim of the present work is to develop a constitutive model that predicts the plastic anisotropy in BCC structured metals, by concentrating on the effect of the microstructure evolution during the load path changes.

Modeling strategy
Modeling starts with a proper description of dislocation movement. A crystal plasticity framework is implemented and validated for this purpose. Peculiar features of BCC crystals are integrated in the model.

Composite Cell Model
Strain path change effects physically originate from a complex microstructure evolution. The present work deals with the contribution of the evolution of dislocation cell structures to these effects.

The material with embedded cells is modelled to behave like a composite consisting of hard cell walls and soft cell interiors. Evolution of internal variables, \( \rho_w \), \( \rho_c \), \( w \), and \( r \) reflects the changes in the microstructure (see figure 3).

The macroscopic response of the model is obtained by applying Taylor averaging and the rule of mixtures:

\[
\sigma = f \sigma_w + (1-f) \sigma_c
\]

where \( f \) is the volume fraction of the cell walls.

Future work
The composite cell model gives reasonable results in a von Mises plasticity framework for the basic strain path changes such as, cross and Bauschinger tests.

Future goal is to simulate the mentioned anisotropic stress-strain responses of BCC crystals in the crystal plasticity framework.
Goal-oriented adaptivity for steady fluid-structure interaction

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Introduction

Numerical simulations of fluid-structure interaction typically requires vast computational resources. Adaptive finite-element techniques could offer a substantial improvement in the efficiency of such simulations.

Model problem

We consider Stokes flow in a flexible tube $\Omega_\alpha$, where the vertical displacement $\alpha$ of the upper wall $\Gamma_\alpha$ satisfies a string equation:

Find $(u, p, \alpha)$ such that

\[
\begin{align*}
-\Delta u + \nabla p &= 0 \\
-\nabla \cdot u &= 0 \\
-\alpha'' &= (-\nabla u \cdot n + p n) \cdot (0, 1) 
\end{align*}
\]

in $\Omega_\alpha$

on $\Gamma_\alpha$

Goal-oriented error estimation

Goal-oriented adaptive finite-element methods rely on a posteriori error estimates of quantities of interest. For this a well-established framework exists for generic boundary value problems [1,2]. However, the free-boundary character of fluid-structure interaction forms a fundamental complication in obtaining such error estimates.

Reference domain method

By introducing an $\alpha$-dependent map $T_\alpha : \Omega_{\alpha h} \to \Omega_\alpha$, we essentially transport our problem from the variable domain $\Omega_\alpha$ to the fixed domain $\Omega_{\alpha h}$. By linearizing the involved functionals, this yields an appropriate dual problem in the complementing dual variables $(z, q, \zeta)$ [3].

Dual problem boundary condition

The dual structure displacement $\zeta$ acts as a Dirichlet boundary condition for the dual fluid velocity $z$, i.e., primal roles have switched. An example dual velocity solution is depicted in the figure below, where the quantity of interest is the average structure displacement $\int_{\Gamma_0} \alpha$.

Numerical results

We discretize the Stokes problem with Taylor-Hood elements and the string problem with linear finite elements. We solve the corresponding dual problem on the approximate domain $\Omega_{\alpha h}$ using the same mesh but the dual shapefunctions are of one order higher.

Error estimate

The figure below shows the convergence of the error estimate (green) and the true error (red) versus the number of degrees of freedom.

Adaptive refinement

The goal-oriented error estimate can straightforwardly be introduced in an adaptive refinement procedure. The figures below show sample meshes obtained using adaptive refinement and uniform refinement and illustrate the efficiency gained for this problem.

References

Quantitative fault discontinuity modeling using the Partition of Unity Method

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Introduction

Accurate quantitative knowledge of the current state of stress in fault areas is of key importance in the assessment of seismic hazard. Regions of high Coulomb stress have been shown to correlate closely with the location and orientation of subsequent seismic events [1]. Modeling these stresses, however, involves computational complexities due to the discontinuous nature of fault systems. The Partition of Unity Method has been developed in the field of fracture mechanics to deal with problems of similar kind, and is expected to proof its value in geophysics as well.

Partition of Unity Method

To solve a differential equation \( L\phi = 0 \), the conventional Finite Element approach is to narrow the solution space by dividing the domain \( \Omega \) into a finite number of subdomains – the elements, and defining on those a number of continuous shape functions \( h_i \). The Finite Element solution \( \tilde{\phi} \) is the unique combination of shape functions that satisfies the Galerkin orthogonality condition,

\[
\tilde{\phi} : \Omega \rightarrow \sum_i h_i \tilde{\phi}_i, \quad \forall \int_\Omega h_j L \tilde{\phi} \, d\Omega = 0.
\]

The narrowed solution space thus defined as the span of continuous shape functions contains continuous solutions only. In situations where the solution can be expected to contain or develop discontinuities this subspace does not suffice. The Partition of Unity Method is an enhancement to standard Finite Element Methods to make it suitable for problems with embedded discontinuities. Unlike most competing methods it does not rely on expensive remeshing; instead it uses the unmodified, continuous shape functions to represent a discontinuous field. This is achieved by incorporating a Heaviside function that takes on different values on either side of the discontinuity. Galerkin’s orthogonality condition – the integral, separates in two sub-integrals over the disjoint subdomains,

\[
\tilde{\phi} : \begin{cases}
\Omega^+ \rightarrow \sum_i h_i \left( \tilde{\phi}_i + H \tilde{\phi}_i \right), \quad \forall \int_{\Omega^+} h_j L \tilde{\phi} \, d\Omega = 0 \\
\Omega^- \rightarrow \sum_i h_i \left( \tilde{\phi}_i - H \tilde{\phi}_i \right), \quad \forall \int_{\Omega^-} h_j L \tilde{\phi} \, d\Omega = 0.
\end{cases}
\]

Initial results

Figure 2 shows a plane of constant dislocation cutting the elements under a small angle, and the stress response in a direction parallel to that plane. Interpreted as a fault system this is a strike-slip fault, and the Coulomb stress to the right can be related to aftershock risk. Future work will focus on applying the Partition of Unity Method to more realistic, three-dimensional fault systems.

References