INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

TOPOLOGY OPTIMIZATION IN MECHATRONIC SYSTEMS

Albert Albers[1], Jens Ottnad[1], Johannes Minx[1] and Pascal Häußler[2]
[1]IPEK - Institute of Product Development, University of Karlsruhe (TH)
[2] FE-DESIGN GmbH Karlsruhe

ABSTRACT
In this paper a new optimization process for the topology optimization of structural parts in controlled dynamic mechanical systems is presented. Different analysis domains, namely hybrid multibody system dynamics (MBS), finite element analysis (FEA), control system simulation and topology optimization are integrated into a straightforward, automatic way. The process allows the topology optimization of structural parts within the controlled MBS with a full coverage of the coupling effects between the dynamic properties of the part, the mechanical system and the control system.
The paper starts with an introduction and a brief review of the basic theory and methods involved in the presented work. In the next section the methodology of the new optimization process is explained in detail. Especially the dynamic interaction between the subsystems and the resulting non-constant optimization boundary conditions as well as their implications on the topology result are investigated.
An illustrative example is employed to demonstrate the feasibility and the potential of the integrated optimization process. The work presented has been done in the frame of the DFG collaborative research centre 588 – "Humanoid Robots". In future, the presented methodology is to be applied to a complex humanoid robot model.

Keywords: Multibody simulation, topology optimization, controlled system, robotics

1 INTRODUCTION
During the last two decades the competition has clearly aggravated in many markets. Effects of globalization and therewith the worldwide growing competition led to a dramatic reduction of many product lifecycles. Companies are forced to shorten the development times of their products and cut the emerging costs while ensuring quality at the same time. The multitude of product recalls in the automotive industry reveals how difficult it is to meet these requirements.
An important approach for enterprises to be successful in this contradictory context is to utilize simulation tools in product development. The aim is to gather information about the product's behavior during early stages of the development. This helps to avoid expensive and time-consuming failures in later phases of the development process.
Today, the usage of simulation tools is common practice in many fields of product development. Finite element analyses (FEA) are widely used regarding mechanical components, for example. Multibody system simulation is employed to investigate the dynamics of mechanical and mechatronic systems. In this field, the integration of body elasticity became of major importance. This led to more realistic MBS simulations and provided information on body loadings for structural analysis and optimization. Combining MBS with tools for the simulation of control systems allows the efficient simulation of mechatronic systems. So-called co-simulation approaches allow to couple solvers for the mechanical and the control system part.
Structural optimization methods play an increasing role in product development. Topology optimization, for example, is widely used to derive design proposals for structural parts in early development stages. By integrating MBS simulation into structural optimization processes parts in mechatronic systems can be optimized regarding the interaction between the parts mechanical properties and the overall system dynamics [1,2].

In this paper an extended topology optimization scheme is presented that integrates a controlled MBS simulation into the optimization process as proposed in [3]. The scheme, for the first time, allows the topology optimization of a body within an MBS taking all emerging loads and the effects of the control system into account. In future, the presented methodology is to be applied to selected parts of a complex humanoid robot model as introduced in [4].

2 BASIC CONCEPTS

2.1 Topology optimization

Topology optimization is used for the determination of the basic layout of a new design. It involves the determination of features such as the number, location and shape of holes and the connectivity of the domain. A new design is determined based upon the design space available, the loads, possible bearings and materials of which the component is to be composed of [5].

Today topology optimization is very well theoretically studied [6] and also a very common tool in the industrial design process [7]. The designs obtained using topology optimization are considered as design proposals. These topology optimized designs can often be rather different compared to designs obtained with a trial and error design process or designs obtained upon improvements of existing design as can be deduced from the motor carrier example in figure 1:

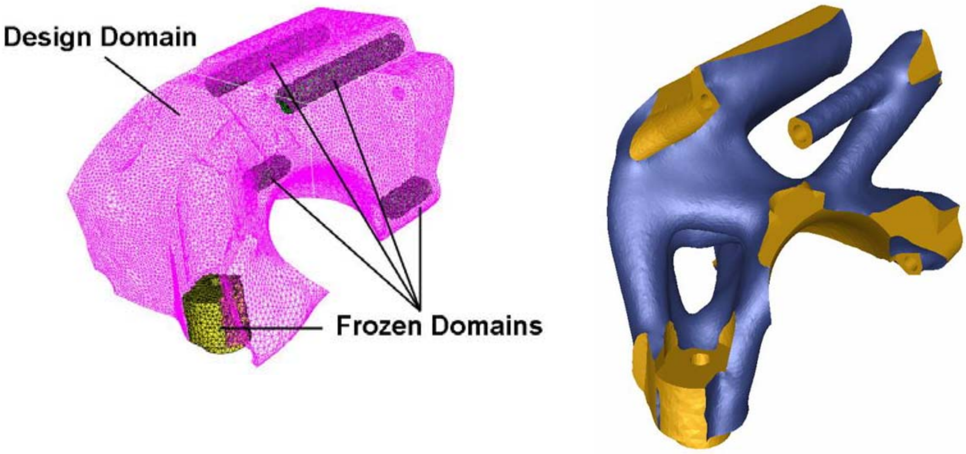

Figure 1: Topology optimization of a motor carrier provided by DaimlerChrysler

The standard formulation in topology optimization is often to minimize the compliance corresponding to maximize the stiffness using a mass constraint for a given amount of material. Compliance optimization is based upon static structural analyses, modal analyses or even non-linear problems e.g. models including contacts.

2.2 Hybrid multibody systems

Hybrid multibody systems combine MBS and FEA approaches. Their fields of application are systems where only small elastic deformations occur in a single structural part. If non-linear effects due to material properties or large deformations are not a relevant factor, the elastic parts can then be described by component mode synthesis. This procedure is an approximation method that allows to approximate the displacement field $\mathbf{u}$ of the deformed part at the time instant t by a weighted sum of constant shape vectors $\boldsymbol{\varphi}$:

$$\mathbf{u}(t,\mathbf{r}) \approx \sum_{i=1}^{N} c_i(t) \cdot \boldsymbol{\varphi}_i(\mathbf{r}) \tag{1}$$

The time dependence of the deformation is only included in the scalar weighting factors or "amplitudes" $c_i(t)$. Inserting the approximation (1) into the well known differential equation of motion

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F} \tag{2}$$

and multiplication with $\boldsymbol{\varphi}_j^T$ (from left) yields:

$$\sum_{i=1}^{N} \ddot{c}_i \boldsymbol{\varphi}_j^T \mathbf{M} \boldsymbol{\varphi}_i + \sum_{i=1}^{N} c_i \boldsymbol{\varphi}_j^T \mathbf{K} \boldsymbol{\varphi}_i = \boldsymbol{\varphi}_j^T \mathbf{F} \qquad (3)$$

Typically a set of mutually orthogonal shape vectors is used in (1). This orthogonality property implies

$$\boldsymbol{\varphi}_j^T \boldsymbol{\varphi}_i = \delta_{ij} \qquad (4)$$

and leads to a decoupling of the single differential equations in (3). The result is a decoupled set of *N* differential equations in the modal amplitudes $c_i(t)$:

$$\begin{array}{ccccc} \ddot{c}_1 m_1 & + & c_1 k_1 & = & f_1 \\ \vdots & & \vdots & & \vdots \\ \ddot{c}_N m_N & + & c_N k_N & = & f_N \end{array} \qquad (5)$$

Here m_i, k_i are the generalized mass and stiffness respectively.

With this approach, the number of degrees of freedom for the description of the deformation of the part is substantially decreased, namely to the number of shape vectors *N* and an efficient, transient dynamic simulation of total systems is made possible.

Eigenvectors in combination with so-called static correction modes are suitable as shape functions. In 1968, Craig und Bampton proposed this procedure in [8] and many commercial software packages use this procedure or slightly modified variants for the modeling of elastic bodies in MBS systems. If the approach in (1) is used for each part in relation to a body-fixed system of coordinates (floating frame of reference), complex systems consisting of several elastic bodies, which carry out large relative displacements in the space, can be effectively simulated. Shabana gives a comprehensive description of this procedure in [9].

2.3 Control and multibody systems

For the simulation of mechatronic systems it is necessary to consider mechanical aspects as well as the behavior of the control system. In the field of simulation there are mainly three ways to couple the models of the two domains.

Direct integration of control systems into a mechanical model or vice versa results in a equation system that is solved by one single solver. This normally leads to fast calculating times; however, today there is only a limited range of functions in the commercial software systems.

The state of a system can be described by means of a set of differential equations which enables an exchange via state matrices.

$$\begin{array}{ll} \dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) & \textit{Equation of states} \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) & \textit{Output equation} \end{array} \qquad (6)$$

Here are:

$\mathbf{x}(t) = \begin{bmatrix} x_1(t) & x_2(t) & \cdots & x_n(t) \end{bmatrix}^T$ *State vector*

$\mathbf{u}(t) = \begin{bmatrix} u_1(t) & u_2(t) & \cdots & u_m(t) \end{bmatrix}^T$ *Vector of input signals*

$\mathbf{y}(t) = \begin{bmatrix} y_1(t) & y_2(t) & \cdots & y_p(t) \end{bmatrix}^T$ *Vector of output signals*

$\mathbf{A}$ *Dynamical or system matrix with the dimension* $[n \times n]$

$\mathbf{B}$ *Input matrix with the dimension* $[n \times m]$

C *Observer matrix with the dimension* $[p \times n]$

D *Passage matrix with the dimesion* $[p \times n]$

By defining the input and output parameters in a mechanical system e.g., it is possible to release the matrices (***A*** to ***D***) after a MBS simulation. However, for this approach linear or linearized systems are required. There are various approaches for linearization that allow to derive state matrices that are selected around well-defined points of operation while flexible FE structures still are subject of the research [10].
A co-simulation provides the opportunity to consider non-linear effects in a system. Equations of the mechanical and control system are each solved by a separate solver. At discrete time steps in the simulation data is exchanged between the solvers according to pre-defined interfaces. A possible input parameter in a mechanical model is, for example, a driving torque while the position of bodies is a usual output parameter.

3 A TOPOLOGY OPTIMIZATION PROCESS FOR CONTROLLED MULTIBODY SYSTEMS

3.1 Methodology

A “traditional” topology optimization scheme as depicted in figure 2 (left) is basically an iterative process that integrates a finite element solver and an optimization module. Based on a design response supplied by the FE solver like strain energy for example, the topology optimization module modifies the FE model.

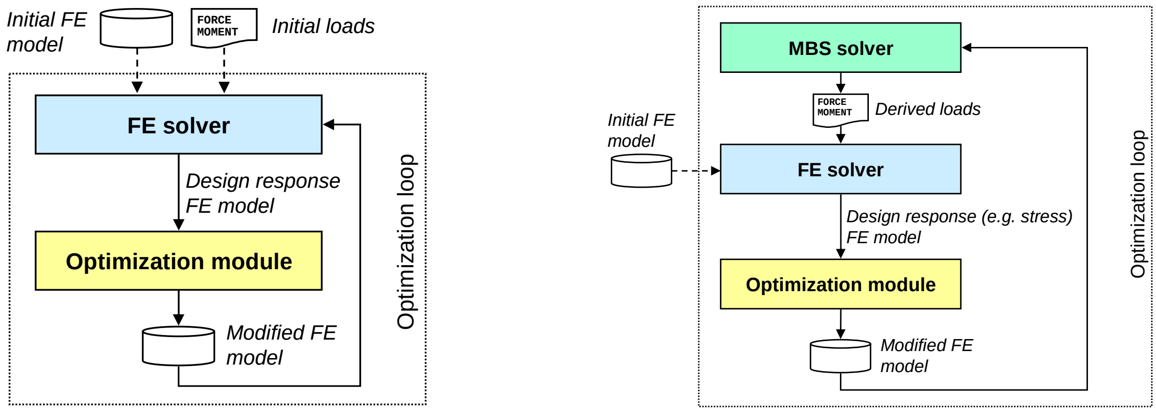

Figure 2: “Traditional” topology optimization scheme (left) and MBS extended scheme (right)

The FE model typically is used together with a set of loads that are applied to the model. In the traditional scheme these loads do not change during the optimization iterations. An MBS extended scheme as introduced by [2] can be employed to take the dynamic interaction between the FE model and the MBS system into account. In figure 2 (right) one can clearly see that the load set is now determined anew in every optimization iteration by means of the MBS simulation. With this approach a body can be optimized “within” it’s surrounding mechanical system without neglecting coupling effects between the body’s and the system’s dynamic properties. This is of great importance since the body’s changing mechanical properties – caused by the optimization algorithm – may affect the system’s overall behavior which in turn may change the loads acting on the body.
In this paper controlled dynamic systems, namely mechatronic systems are considered. A control system adds additional dynamic properties to the MBS. The coupling between the mechanical system and the control system might influence the overall system’s dynamic behaviour significantly. As a consequence, loads that act on a body in the system might be affected not only by the geometric changes due to optimization but also by the control system as well.

In order to carry out a topology optimization, the MBS extended optimization scheme must be extended again by means of integrating the control system as depicted in figure 3.

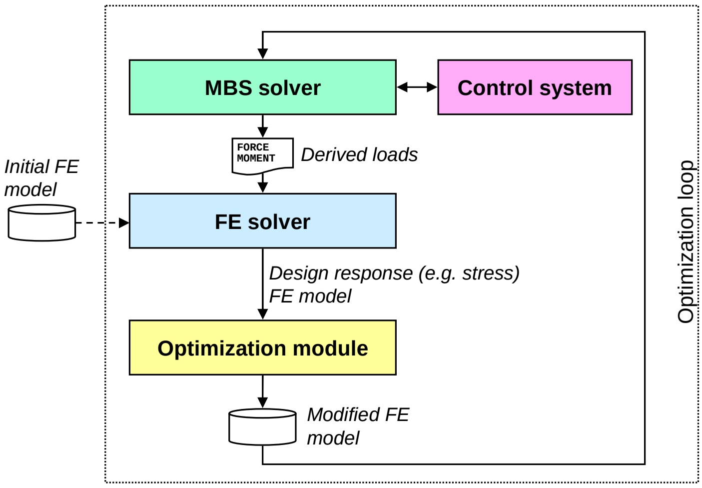

Figure 3: Controlled MBS extended topology optimization

The co-simulation of the mechanical system and the control system covers the complete coupled dynamics of the mechatronic system. From this simulation a new, “updated” set of loads can be derived for a body in the system. In the topology optimization scheme this is done within every optimization iteration. This approach provides realistic loads during the optimization and covers all possible changes in the acting loads caused by any of the coupling effects explained above.

3.2 Implementation

The new topology optimization scheme has been implemented with the optimization code TOSCA from the company FE-DESIGN (see figure 4). For the controlled MBS simulation, MSC.ADAMS from MSC.Software Corporation has been used in co-simulation mode together with MATLAB provided by The MathWorks. The complete process flow as well as all necessary input/output handling is completely automated. A topology optimization of a body “within” its mechatronic system can now be carried out straightforward.

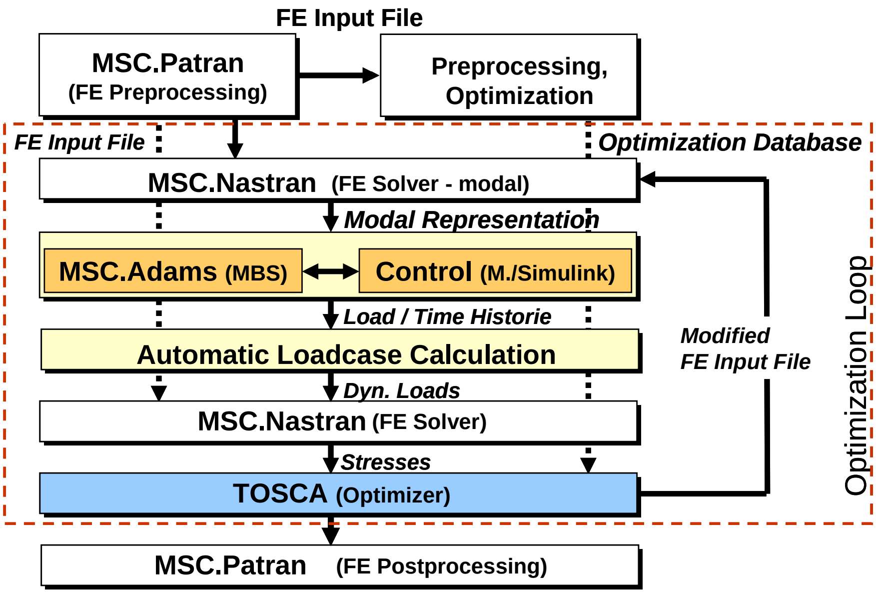

Figure 4: Automated process of extended topology optimization

4 EXAMPLE

4.1 Model setup

The optimization scheme introduced in this paper is to be applied to a humanoid robot within the DFG collaborative research centre 588 – “Humanoid Robots” [11]. The simple model presented in this section is a subset of the ARMAR III forearm. ARMAR III is the latest version of the demonstrator system of the collaborative research centre 588 (see figure 5). The rectangular aluminium profile (cross-section 40 x 40 mm²) of the beam (length 300 mm) is investigated and represents the design space of the arm’s support structure.

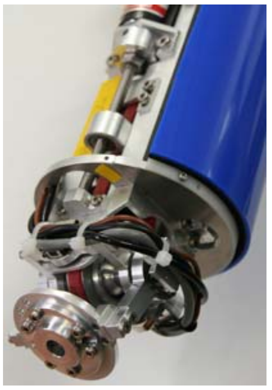

Figure 5: Forearm of ARMAR III

The FE Model of the flexible arm consists of uniform Hex8 elements and has two interface points that are modelled as “Rigid-Body-Elements” (MSC.Nastran type RBE2). These points are used to connect the arm to the surrounding MBS. The load applied at the tip of the arm has a mass of about 3.5 kg. (= mass of the hand plus an object which ARMAR III can move dynamically.
The simplified system of this first stage of investigation is limited to one degree of freedom that enables a rotation of the arm as described in figure 6.

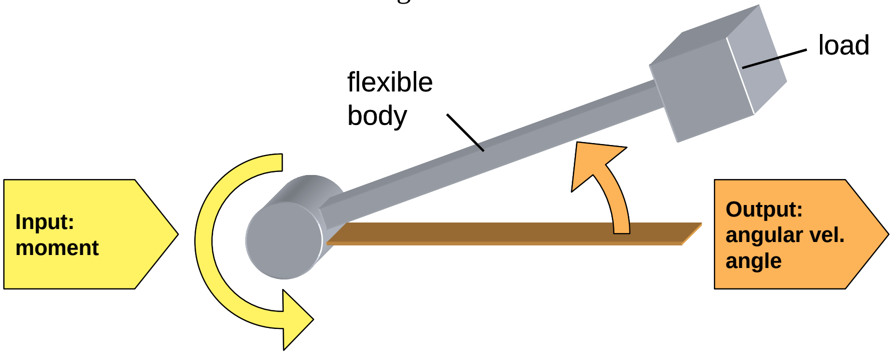

Figure 6: Mechanical setup with interfaces to the control system

This simplification is justified because at this stage the focus of the investigations lies on the methodology of the optimization scheme itself. A torque is used as an input parameter and the angle/angular velocity of the arm are used as output parameters in order to control the system. The control system uses a PID controller and has a step function as input value. For the tuning of the controller parameters, state matrices were used as representation of the mechanical system. These matrices were generated by a reduced mechanical model set up with rigid bodies.

4.2 Results

The goal of the topology optimization of the arm was to maximize the stiffness using a mass constraint that reduces the mass to 30 % of the original design space. Figure 7 shows the result of the topology optimization of the arm in the controlled dynamical system.

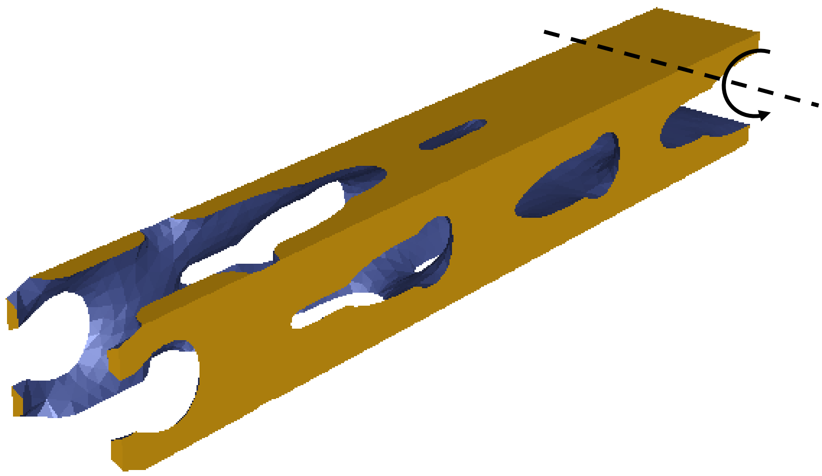

Figure 7: Topology optimization result of the arm support structure

The optimized design is a kind of a hollow profile which is typical for lightweight structures subject to bending loads. Of course, this optimized structure is not stiff with respect to rotations or toques acting around the longitudinal axis. For a more realistic optimization of the robot's arm support structures it will be necessary to use a realistic MBS system that is capable of all the intended arm movements. A much higher variety of the load cases will then be the consequence.

An important difference of the topology optimization of parts in such controlled dynamic systems compared to a traditional optimization is that the loads change through the iterations. This aspect can even be recognized at this simple model by taking a look at the control system behavior. Figure 8 depicts the characteristics of the control system, where the optimized mechanical structure moves faster and shows less overshoot. Regarding the consumed energy the optimized arm has advantages whereas the start design is better in the intermediate phase of the overall movement.

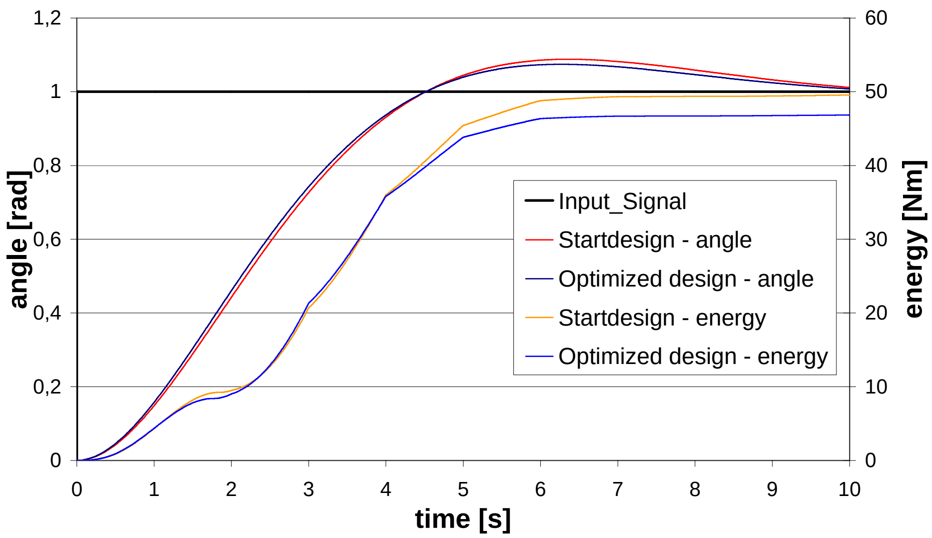

Figure 8: Comparison of the start design and the optimized arm

Of course, the "mechanical" optimization of a part within the controlled MBS might lead to a badly adjusted control system. For an improved performance of the whole mechatronic system, an optimization of the mechanical parts and the control system in one process covering all the interaction will be necessary. A first step is an adoption of the controller parameters throughout every single iteration of the topology optimization. This approach is currently under investigation.

5 SUMMARY AND CONCLUSION

In this paper a new optimization process for the topology optimization of structural parts in controlled dynamic mechanical systems has been presented. Different analysis domains, namely hybrid multibody system dynamics (MBS), finite element analysis (FEA), control system simulation and topology optimization are integrated into a straightforward, automatic way. The process allows the topology optimization of structural parts within the controlled MBS with a full coverage of the coupling effects between the dynamic properties of the part, the mechanical system and the control system. Of great importance is the update of the loads within every iteration of the topology optimization.

For an optimization of the whole mechatronic system some suitable sort of adaptation of the control parameters within every optimization iteration has been suggested. This further extension of the process will be realized by a second optimization loop which will be embedded into the topology optimization process. The presented optimization scheme will be applied to more complex robot models in future work.

REFERENCES

[1] Minx, J.; Häußler, P.; Albers, A.; Eemmrich, D.; Allinger, P.: „Integration von FEM, MKS und Strukturoptimierung zur ganzheitlichen, virtuellen Entwicklung von dynamisch beanspruchten Bauteilen", NAFEMS seminar, analysis of multibody systems with FEM and MBS, October, 27th -28th, 2004 in Wiesbaden

[2] Häußler, P.; Emmrich, D.; Müller, O.; Izhöfer, B.; Nowicki, L.; Albers A.: Automated Topology Optimization of Flexible Components in Hybrid Finite Element Multibody Systems using ADAMS/Flex and MSC.Construct, ADAMS European User's Conference, Berchtesgaden, Germany, November 14-15, 2001

[3] Häußler, P.: Ein neuer Prozess zur parameterfreien Formoptimierung dynamisch beanspruchter Bauteile in mechanischen Systemen auf Basis von Lebensdaueranalysen und hybriden Mehrkörpersystemen, dissertation at the faculty for engineering, research reports of the Institute for Product Development, Volume 20, University of Karlsruhe 2005, ISSN 1615-8113

[4] Albers A., Brudniok S., Ottnad J., Sauter Ch., Sedchaicharn K.: Upper Body of a new Humanoid Robot – the Design of ARMAR III, Humanoids 06 - 2006 IEEE-RAS International Conference on Humanoid Robots, December 4 to 6, 2006 in Genova, Italy

[5] Friedrich, M.: Das Beste vom Rechner - Überblick Strukturoptimierungsmethoden in der industriellen Anwendung, CADplus, September 2006, page 40 et seq.

[6] Bensoe, M.; Sigmund, O.: Topology Optimization – Theory, Methods, Application, Springer Verlag 2003

[7] Pedersen, C.B.W.; Allinger, P.: Recent Developments in the Commercial Implementation of Topology Optimization. TopoptSYMP2005 - IUTAM-Symposium- Topological design optimization of structures, machines and material – status and perspectives. Copenhagen, Denmark, 123-132, 2005

[8] Craig, R. R.; Bampton, M. C. C.: Coupling of Substructures for Dynamic Analyses, AIAAJournal Volume 6, No. 7, July 1968

[9] Shabana, A. A.: Dynamics of Multibody Systems, Cambridge University Press, 1998

[10] Ortiz J., Bir G.: Verification of New MSC.ADAMS Linearization Capability ForWind Turbine Applications, 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno, Nevada

[11] Webside SFB588: www.sfb588.uni-karlsruhe.de

Contact: o. Prof. Dr.-Ing. Dr. h. c. Albert Albers
University of Karlsruhe (TH)
Institute of Product Development
Kaiserstraße 12
76131 Karlsruhe
Germany

Phone: +49 (721) 608 2371
Fax: +49 (721) 608 6051
e-mail: albers@ipek.uni-karlsruhe.de
URL: www.ipek.uni-karlsruhe.de

Contact: Dipl.-Ing. Jens Ottnad
University of Karlsruhe (TH)
Institute of Product Development
Kaiserstraße 12
76131 Karlsruhe
Germany
Phone: +49 (721) 608 7066
Fax: +49 (721) 608 6051
e-mail: ottnad@ipek.uni-karlsruhe.de
URL: www.ipek.uni-karlsruhe.de

Contact: Dipl.-Ing. Johannes Minx
University of Karlsruhe (TH)
Institute of Product Development
Kaiserstraße 12
76131 Karlsruhe
Germany
Phone: +49 (721) 608 2578
Fax: +49 (721) 608 6051
e-mail: minx@ipek.uni-karlsruhe.de
URL: www.ipek.uni-karlsruhe.de

Contact: Dr.-Ing. Dipl.-Phys Pascal Häußler
FE-DESIGN GmbH
Haid-und-Neu-Straße 7
76131 Karlsruhe
Germany
Phone: (+49) 721 96467-0
Fax: +49 (721) 96467-290
e-mail: pascal.haeussler@fe-design.de
URL: www.fe-design.de