Karlsruhe Institute of Technology

Extended Topology Optimization - two factors to decrease energy consumption of structural parts during dynamic movements

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by C. Sander, D. Petrich and A. Albers[1]

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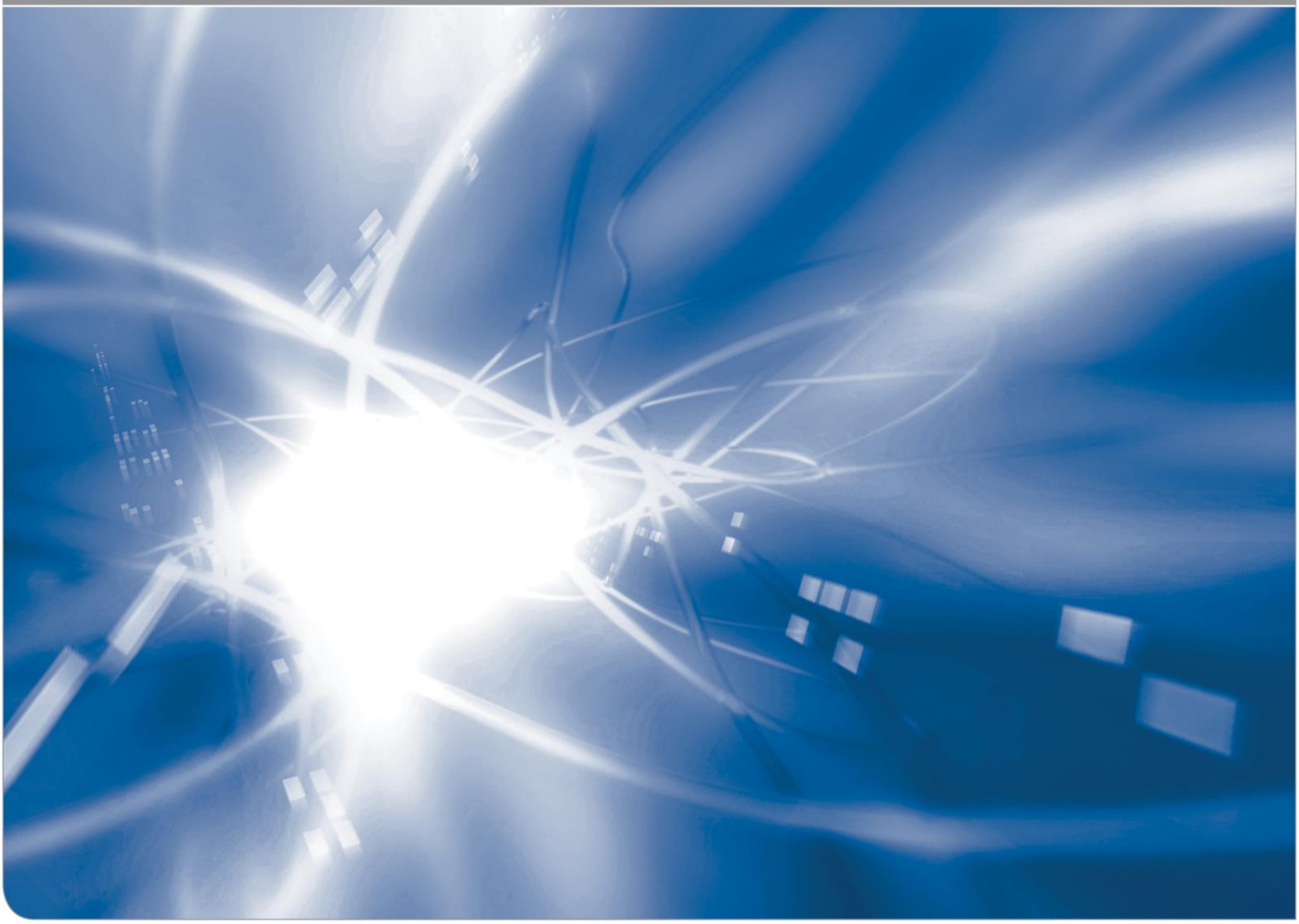

facultative

[1] IPEK - Institute of Product Engineering

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Abstract

With increasing concerns over the excessive consumption of primary energy and the resulting environmental pollution, lightweight design is a great opportunity to reduce energy usage of parts in dynamic (accelerated) systems. This contribution deals with an extension of the classical topology optimization by two factors to decrease energy consumption during dynamic movements. To evaluate the extension different trajectories of mechanical structures in space are taken into account (not part of the optimization) to get a design proposal for a lightweight design for dynamic (accelerated) systems. Using a multi-body system of a robot arm (4 DoF) the energy efficiency of the mechanical structure and the descriptive criteria can be calculated. In this contribution it will be shown that, depending on the movement and on which of the approach is used, the developed algorithm is capable to increase the energy efficiency of a mechanical structure. A reduction of up to 6% of the kinetic energy for moving the part in different trajectories, compared to a traditionally optimized part with the same mass, can be achieved by a different specialized material distribution. This paper is a detailed contribution of the paper presented at NAFEMS 2012 in Bamberg [18].

1 INTRODUCTION

The global energy usage has grown by the factor of 26 per capita over the past 200 years [21] as shown in figure 1. With increasing concerns over this excessive consumption of energy, new methods must be developed to reduce greenhouse gas emissions and to stop climate change. Different technology options like renewable energies and energy efficiency can be used to reduce greenhouse gas emissions. Energy efficiency can be defined as the percentage of the total energy input to a technical system that is consumed in useful work and not wasted - mostly useless heat. The optimum level of energy efficiency is thus achieved when the benefit is met with as little energy as possible. The highest impact in emission reduction contributions can be achieved by increasing the energy efficiency of future products, processes, etc. [21]. Therefore the European Union, several nongovernmental organizations and the economy have set the goal to significantly increase the efficiency of the used resources in areas, such as living, transportation, energy production and industry, within the next years. The largest sector in Germany where primary energy is needed is the industry (2005)[14]. Here a small increase of energy efficiency has a great impact in the reduction of the total primary energy used.

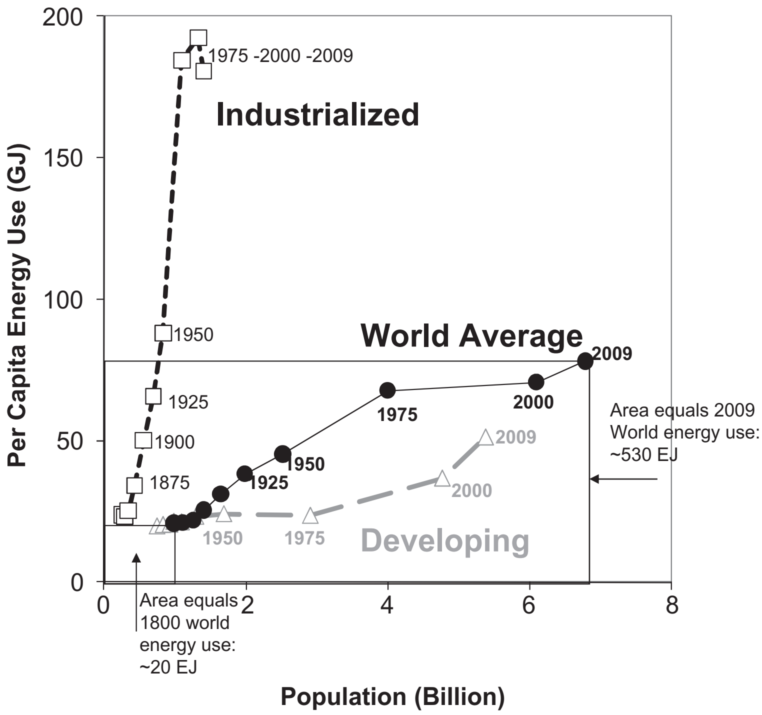

Figure 1: Growth per capita of energy use and population (1800-2009). Source data: Grubler (2008, updated using BP, 2010; IEA, 2010). Data prior to 1950 are estimates. Source figure: Wilson and Grubler (2011) [21]

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A great challenge for researchers is to create new methods and to define new processes to be able to find hidden potential for resource and energy savings in technical systems in the future. To achieve this goal, it is inevitable to simulate the functioning of a technical system and to be able to optimize it. In the system-based structural optimization the best possible structure of a part can be calculated so that the overall behavior of the system and the interactions of system elements are taken into account. An important method to calculate design proposals for certain boundary conditions and in a given design space is the computer-aided topology optimization, which is superior, especially for complex components and load situations compared to traditional design rules with an intuitive approach. Existing methods normally consider external and internal loads, manufacturing constraints like e.g. demolding control. But normally these methods have the goal to find a stiff and lightweight structure without taking the energy efficiency of the system directly into account. These components are normally more energy efficient, compared to the standard design, but they are not optimized considering the dynamic behavior during the movement of the part. This means that, depending on the kinematic of a spatially active multi-body system, it may be useful to adapt the material distribution of the part to avoid very large moments of inertia which reduces the energy efficiency of this part during dynamic movements.

In this paper an extension of the classical topology optimization is shown. This paper is a detailed contribution of the paper presented at NAFEMS 2012 in Bamberg [18]. Here, different spatial trajectories of mechanical structures are taken into account to calculate a design proposal for a lightweight design for dynamic (accelerated) systems. Using a multi-body system of a robot arm (4 DoF) the energy efficiency of the mechanical structure and two descriptive criterion can be calculated. Two reference values were specified as process parameter to adapt the properties of each finite element in the design area for the topology optimization.

2 STATE OF THE ART

In modern product development the usage of simulation tools is common practice today. To analyze stress and strain in mechanical components the finite element analyses (FEA) is widely used, for example. To investigate the dynamic behavior of mechanical and mechatronic systems multi-body simulations (MBS) are used. The integration of body elasticity led to more realistic MBS and information about loads acting on bodies for structural analysis and optimization. Additionally structural optimization methods play an increasing role in modern product development. Topology optimization [6] is used to derive design proposals for a lightweight design for structural parts in early development stages. This method is successfully used in the automotive and aerospace industry as well as in the design process of consumer products [19, 16]. By integrating MBS simulation into structural optimization processes bodies in dynamic systems can be optimized regarding the interaction between the body's mechanical properties and the overall system dynamics [9, 8, 13]. In [3] an optimization process for the topology optimization of flexible bodies in controlled dynamic mechatronic systems is discussed. This optimization process was even extended to an integrated topology optimization method of flexible bodies in controlled dynamic mechatronic systems where the control parameters are also optimized during the hole process [2].

The torque minimization of a two degrees of freedom serial manipulator is presented in the work of Arakelian et. al. [4]. This analytic method is based on a minimum energy control and a redistribution of movable masses. First a optimal trajectory is calculated to reduce energy consumption of the manipulator. In a second step the movable masses are redistributed using a counter weight system. This method leads to a significant reduction of motor torques and an improved kinematic structure. However this approach doesn't help the product developer by designing the supporting structure of each robotic arm.

Scientists of Chemnitz University of Technology and of Fraunhofer Institute for Machine Tools and Forming Technology (IWU) develop lightweight components for energy-efficient machine tools. In their contribution [11] they show that the mass of structural components at machine tools can often be reduced by 30% using optimization tools. This reduction can lead directly to lower electrical power losses of the servo drives in a similar amount or even higher reductions up to 50%, depending on the motor and the dynamics (acceleration). This is a great increase in energy efficiency. An extended topology optimization considering the dynamic behavior and the energy consumption wasn't developed and used for their optimization, what would have increased their total energy reduction additionally.

3 TOPOLOGY OPTIMIZATION

In this section the classical and the extended topology optimization are presented. A topology optimization is used to derive a design proposal of a structural mechanical part. It involves the determination of the shape, location and number of holes and the connectivity of the domain. A new design can be calculated using the available design space, the loads, possible functional surfaces and materials of which the component is to be composed of.

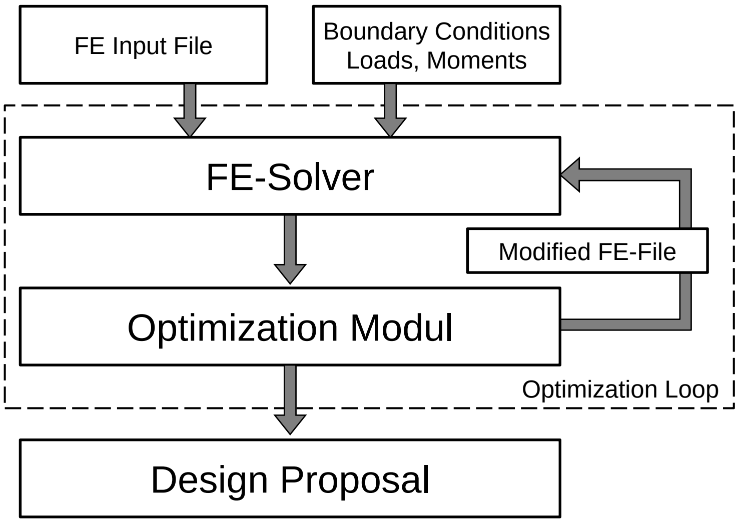

Figure 2: Classical topology optimization process

3.1 Classical Topology Optimization

The topology optimization based on the controller algorithm uses a modified optimality criteria algorithm (oc)[12]. The standard formulation in topology optimization involves the objective of minimizing the compliance with a volume constraint. The compliance is the stain energy of the structure. It can be considered as a reciprocal measure for the stiffness of the structure. The volume constraint specifies the amount of volume is to be removed. This algorithm homogenizes the stress distribution in a part and obtains an optimal load path. Therefore it can be used for stiffness optimization with material constraints. The classical topology optimization process described is shown in figure 2.

First a FEA must be carried out. Second the optimization program starts to read the results of the FEA. From iteration to iteration the properties of each finite element (such as Young's Modulus and density) are modified until the optimization objectives are fulfilled. After 15 optimization iterations it converges even for large models including non-linearities (e.g. contact) and obtains a very clear solid design proposal. However, the constraints and object function are limited to be the material volume and the compliance.

In figure 3 the result of a classical topology optimization for ARMARs[1],[5] next torso is illustrated. The design area results from the free space in the inner region of the torso. Different loadcases were used to calculate the stress distributions and based on these results a smoothed design proposal was calculated using the topology optimization. Using restrictions according the production of the torso, the final design was engineered and the torso produced.

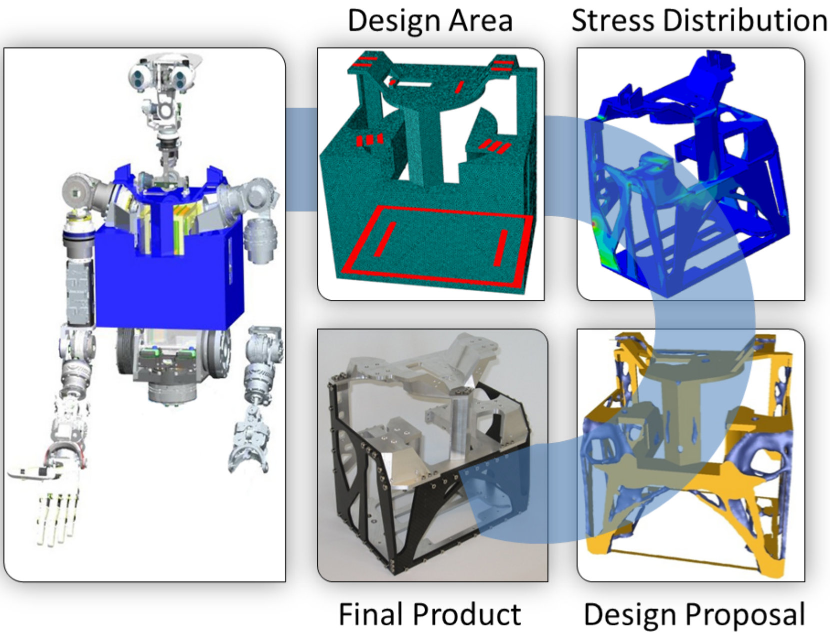

Figure 3: Topology Optimization of ARMARs Torso

3.2 Extended Topology Optimization of Flexible Bodies in Mechanical and Controlled Mechatronic Systems

Albers et al. [3] extended the topology optimization process to take the systems behavior of a mechatronic system into account. In a first step the classical topology optimization was coupled with a MBS. Using a hybrid multi body simulation allows to take the dynamic interaction between the FE model and the MBS system into account. The static load set can been updated during every iteration of the optimization task using the method described by Haeussler et al. [9]. With this approach a flexible body can be optimized in ”it's” mechanical system. The consideration of coupling effects between the body's and the system's dynamic properties are not possible. But this is of great importance since the body's changing mechanical properties caused by the optimization algorithm affect the system's overall behavior which in turn changes the loads acting on the body. Albers et al. [2] analyzed this coherence. Therefore they extended the topology optimization a second time. The hybrid multi body simulation was coupled with a controller using a co-simulation tool. It can be shown that the coupling between the mechanical system and the control system has an influence to the overall system's dynamic behavior. As a consequence, loads that act on a body in the system are not only affected by the geometric changes due to optimization but also by the control system as well.

The topology optimization process for first and second extension as described is shown in figure 4.

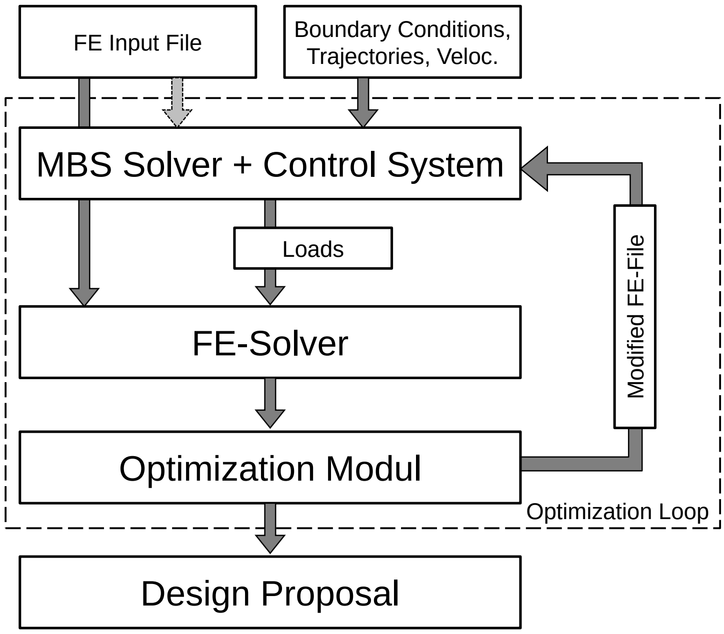

Figure 4: Extended topology optimization process for dynamic systems

4 NEW APPROACH FOR OPTIMIZATION THE ENERGY CONSUMPTION

4.1 Introduction

The new method has to be capable to reduce automatically the energy consumed by the mechanical structure during a dynamic movement, without limiting the functionality in order to increase the energy efficiency. In this context energy is understood to be the potential and kinetic energy stored in the part during a movement. Thus a topology optimization has to be extended to be able to consider the potential and kinetic energy of the part which has to be optimized. In the following chapters an approach is explained how the energy efficiency of a mechanical structure can be characterized in order to derive a criterion for the optimization of the topology.

4.2 Potential Energy

The potential energy of a flexible body, build up of *n* finite elements, is calculated from the sum of the potential energy and the deformation energy (Eqn. 1).

$$V = \sum_{n} V_{FE,g}(\xi) + \frac{1}{2}\xi^{T} \cdot K_{FE} \cdot \xi \tag{1}$$

According to the principle of superposition the total amount of potential energy can only be reduced when both terms are minimized.

The influence of the gravitational effect V_g can only be controlled by path planning algorithms which is common in robotics today [17][15]. The trajectories are given here and not part of the optimization. Furthermore the reduction of the potential energy can be achieved using the methods of topology optimization to reduce the compliance. Therefore the optimization of the potential energy can be achieved by optimizing the deformation energy.

As described, the homogenization of the strain energy is an efficient way to reduce the deformation of a component compared with another component with the same volume, loads and boundary conditions. Therefore, the classical topology optimization can also be seen as an optimization with the objective to reduce the deformation energy and therefor to reduce the potential energy.

4.3 Kinetic Energy

If a metal structure has been optimized to reduce the potential energy by minimizing the amount of deformation, it can be assumed that the kinetic energy can be calculated in a good approximation using a rigid body.

The kinetic energy can be calculated using equation (Eqn. 2).

$$T = \sum_{n} T_{FE,trans} + T_{FE,rot} \tag{2}$$

The formula for the translational kinetic energy is shown in Eqn. 3.

$$T_{FE,trans} = \frac{1}{2} m_{FE} \nu_{FE}^{T} \nu_{FE} \tag{3}$$

And with the formula for the rotational kinetic energy $T_{FE,rot}$ (Eqn. 4) the kinetic energy can be calculated.

$$T_{FE,rot} = \frac{1}{2} \omega_{K,O}^{T} I_{FE} \omega_{K,O} \tag{4}$$

Therefor the kinetic energy can be calculated with(Eqn. 5).

$$T = \frac{1}{2} \sum_{n} m_{FE} \nu_{FE}^{T} \nu_{FE} + \omega_{K,O}^{T} I_{FE} \omega_{K,O}. \tag{5}$$

If a movement should take place within a certain time, whereby the translational and rotational velocity are determined, only two parameters arise from this definition, with which the kinetic energy of a body can be affected. On the one hand it is the total mass *M* of the target structure and on the other hand it is the material distribution in the rotation, which is expressed in the term of the inertia tensor *I*. Now, it can be deduced that the kinetic energy of a dynamic moving part can only be decreased, when it's mass is reduced and it's material distribution is optimized. The optimization algorithm used handles the resulting total mass of the design space as a constraint. Taking into account that every material can only handle a certain and especially limited strain energy density until it is destroyed, the total mass can only be reduced to a certain point. For this reason, the optimization of the "used" kinetic energy of a mechanical structure, can only be improved by the reduction of the required rotational energy for a dynamic motion and a given trajectory.

A general three-dimensional body motion can be split in a translation and a rotation motion around a spatial axis at any time [10]. The motion can thus be described as a plane rotation (at discrete time) with respect to a time-dependent rotation axis. Using this feature, the rotational energy of any body can be described through the following scalar equation (Eqn. 6):

$$T_{rot}(t) = \frac{1}{2} J_k(t) \omega t^2 \tag{6}$$

The tensor for the inertia *I* from equation 4 and 5 has been replaced here by the moment of inertia J_k respective to it's instantaneous rotational axis of the body. It describes the body's resistance against a change in the rotational motion and can be divided into two terms using the set of Steiner [20] (Eqn. 7):

$$J_k = J_{K,s}(t) + m_k d_k(t)^2. \tag{7}$$

From these relations and the mass as a function of the volume $m_{FE} = \rho_{FE} V_{FE}$ the equation of the rotational energy can be derived for *n* finite elements constructed design space (8):

$$T_{rot}(t) = \frac{1}{2} \sum_n [J_{FE,S}(t) + \rho_{FE} V_{FE} d_{FE}(t)^2] \omega(t)^2 \tag{8}$$

With a given angular velocity vector ω*(t)*, the moments of inertia of the finite elements for their center of gravity $J_{FE,S}(t)$ and the rotational inertia for the instantaneous rotation axis $R_T = \rho_{FE} V_{FE} d_{FE}(t)^2$ the rotational energy of a body can be calculated. It can be shown that the effect of inertia $J_{FE,S}(t)$ can be neglected if the individual finite elements are small compared to the overall structure what is normally given because the quality of the design proposal of a classical topology optimization is thereby essential influenced by a fine and even finite element mesh [6]. Using this assumption the rotational inertia R_t is the only relevant parameter that affects the rotational energy of a body made up of n finite elements significantly. The equation (9) is a criterion for the topology optimization based on the kinetic energy and is used in this approach to calculated the factors to adapt the strain energy.

$$T_{rot}(t) = \sum_n R_{T,FE} \omega(t)^2 = \frac{1}{2} \sum_n \rho_{FE} V_{FE} d_{FE}(t)^2 \omega(t)^2 \tag{9}$$

4.4 Implementation

As illustrated before, there are two critical parameters that affect the topology optimization based on the energy efficiency of a mechanical structure during dynamic movements. The influence of the potential energy is taken into account by minimizing the compliance. Using the classical topology optimization normally the strain energy density is the parameter which is used. The influence of the kinetic energy has to be considered separately. The finite elements which are responsible for a strong increase of energy consumption have to be penalized.

The basic idea to integrate a reduction of the kinetic energy, consumed by a structural part, is to define a specific factor which decreases the strain energy for efficient finite elements. Then, the elasticity modulus of these elements, in the sense of optimality criterion, are less reduced by the optimization tool.

The adaptation of the strain energy is based on the energy efficiency modeled by the product of the strain energy of the design area and the adaption factor Q (Eqn. 10):

$$Strainenergy_{new} = Strainenergy_{old} \cdot Q_{adaptation} \tag{10}$$

Here are two different adaption factors presented. One factor is called Q_{RED}. The rotational energy density RED_i has to be calculated for every finite element and every time step of the movement. It can be written as shown in equation 11.

$$RED_i = \frac{RotationalEnergy_i}{V_i} = \frac{1}{2} \rho_i d_i(t)^2 \omega(t)^2 \tag{11}$$

The adaption factor is built by the quotient of the smallest rotational energy of an element in the structure and the rotational energy density of each element. The value of Q_{RED} is between 0 an 1 and can be calculated with equation 12.

$$Q_{RED,i} = \left(\frac{RED_{min}}{RED_i} \right)^q = \left(\frac{(\rho d(t)^2)_{min}}{\rho_i d_i(t)^2} \right)^q \tag{12}$$

The second adaption factor is called Q_{EDW}. It is also calculated by using the energy density (Eqn. 11). But here the strain energy density for each element is divided by the rotational energy density which is called EDW (Egn. 13).

$$EDW_i = \frac{StrainEnergyDensity_i}{RED_i} \tag{13}$$

The adaption factor can be calculated by dividing the EDW of each FE by the greatest EDW in the design space (Eqn. 14).

$$Q_{EDW,i} = \left(\frac{EDW_i}{EDW_{max}}\right)^q \tag{14}$$

In figure 5 the new optimization process for the extended topology optimization for energy efficiency is illustrated.

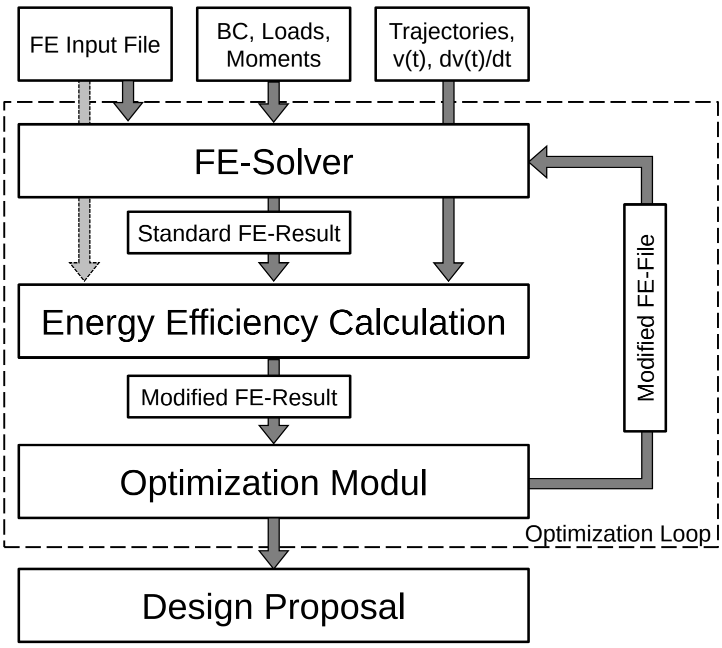

Figure 5: Extended topology optimization process for energy efficiency

5 Example and first Results

5.1 Model setup

The optimization process introduced in this contribution has to be applied to parts of the next generation of the humanoid robot ARMAR[5] which is developed within the collaborative research center 588[1] funded by the Deutsche Forschungsgemeinschaft (DFG). The goal of this project is to generate concepts, methods and concrete mechatronical components for a humanoid robot, which will be able to share his working space with a human partner. With the help of this partially anthromorphic robotic system, it will be possible to step out of the ”robot cage” to realize a direct contact to humans. Using a multi-body system of the robot’s arm (4 DoF) the energy consumption of the mechanical structure and a descriptive criterion can be calculated and a design proposal is

[1] http://www.sfb588.uni-karlsruhe.de/about/

calculated. In figure 6 the used configuration is shown. The lengths of the segments l_1 and l_2 are defined to $500mm$.

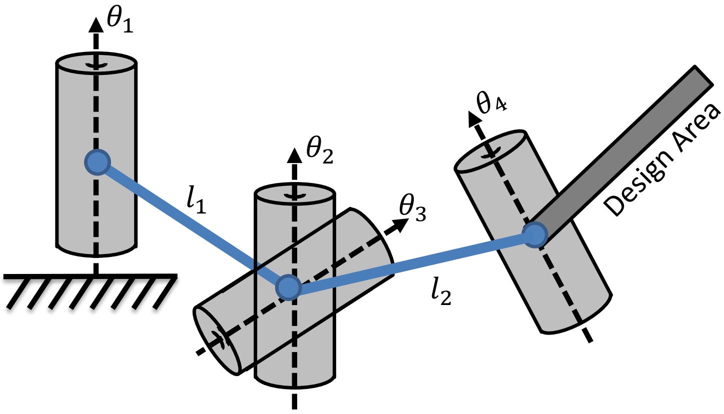

Figure 6: 4 DOF robot arm

The third body (fig. 6 and 7), the design area, has a length of $200mm$, height of $30mm$ and a width of $20mm$. It is meshed with 34.462 second-order tetrahedral elements (CTETRA10) to get a satisfactory stress prediction [7]. The defined material is an aluminum-alloy with $\rho = 2,7 \cdot 10^{-09} \frac{t}{mm^3}$,a Young's modulus of $70.000N/mm^2$ and the Poisson's number of $0,3$.

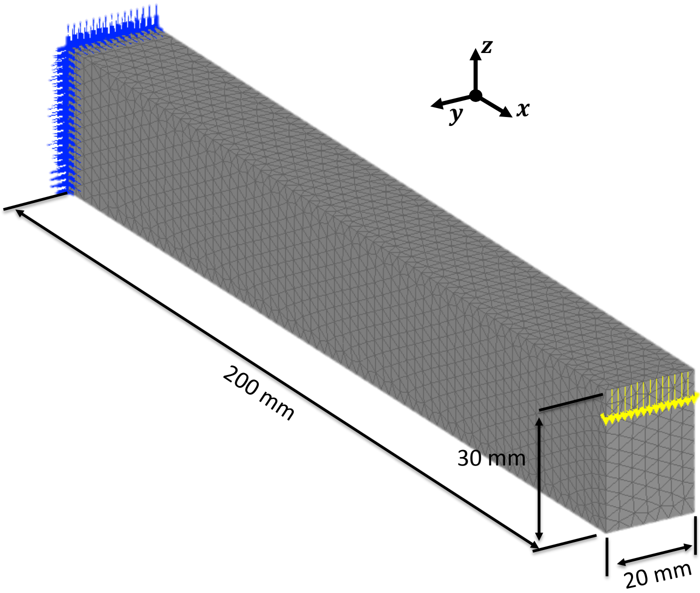

Figure 7: Model of the design area

5.2 Example 1: Academic

In this subsection, an academic example is discussed, where $\theta_n = \dot{\theta}_n = 0, n = 1..3$ and $\dot{\theta}_4$=*0.5*$\cdot\pi\cdot$*t*. In words this restriction is equal to a fixation of the first three degrees of freedom. Therefor the instantaneous axis of rotation was determined by a script. In this way, the distribution of rotational energy density in the design space can be adjusted and tested. The relative positions of the axes of rotation and the resulting distributions of rotational energy densities in the design space is projected onto the respective finite elements and shown in figure 8.

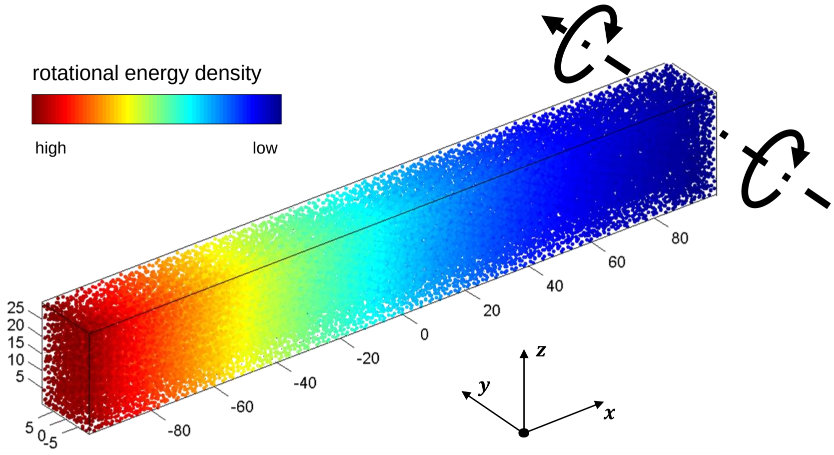

Figure 8: Rotational energy density for an academic example, $\dot{\theta}_4$=0.5·π·t

5.3 Example 2: with Complex Motion

At this motion the multi-body system starts at the time $t = 0$ with the joint angle positions θ_n=*0* from the stretched arm position. All joint centers are then located on a straight line. This initial configuration of the multi-body system corresponds to a spread arm. All joints start at the same time with two different angular velocities for this example. From this two properties it follows that the resulting rotational axis of the design space cuts the straight line connecting the joint centers at the beginning of the simulation. For a short simulation time the rotational energy density at any angular velocities will increase for every finite element in the design space with increasing distance from the fourth joint. This movement is represented in the simulation model shown in figure 9. For this model the angular velocities are defined to $\dot{\theta}_1 = -\dot{\theta}_3 = \pi$ and $\dot{\theta}_2 = \dot{\theta}_4 = -\frac{1}{2}\pi$.

The distribution of the rotational energy density at the described complex motion of the design space is shown in figure 10.

5.4 Example 3: Model for Comparison - Traditional Topology Optimization

To be able to compare the results from the extended topology optimization it is inevitable to have a result for the energy efficiency of traditional optimized parts. Therefor the same design area was used for a traditional topology optimization with the standard load case shown in fig. 7. The adaption factor was set to 1 and therefore all influences by the extension were eliminated.

5.5 First Results

In this subsection the results for the three examples are discussed.
Example 1:
Due to the relatively close position of the rotation axis to the design area and the quadratic dependence of the rotational energy density and the distance to the rotational axis, the field in which the adaptation coefficients are, is relatively large. The new design proposal based on the extended topology optimization (Q_{RED}) is shown in figure 11. When this result is compared with the model

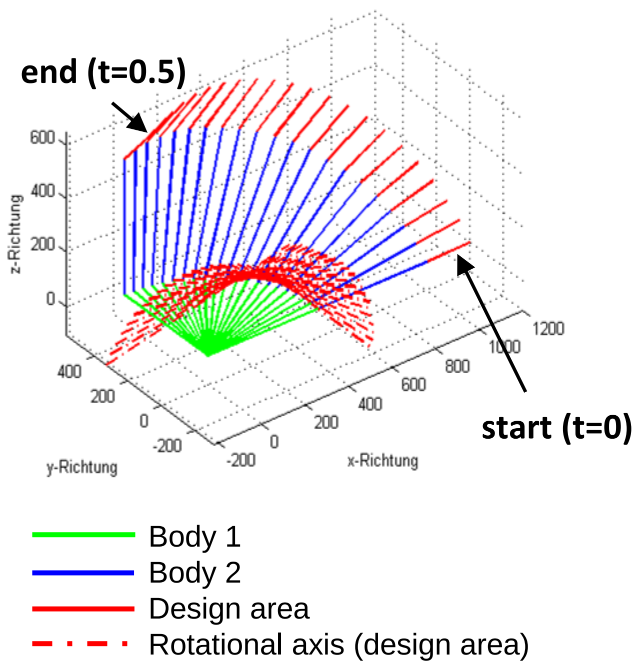

Figure 9: Motion of the design area, $\dot{\theta}_1$=π, $\dot{\theta}_2$=-$\frac{1}{2}\pi$, $\dot{\theta}_3$=-π, $\dot{\theta}_4$=-$\frac{1}{2}\pi$

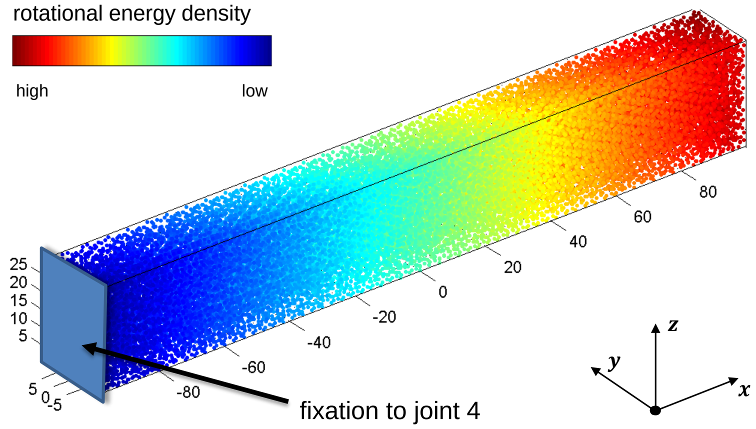

Figure 10: Rotational energy density for a complex motion, $\dot{\theta}_1$=π, $\dot{\theta}_2$=-$\frac{1}{2}\pi$, $\dot{\theta}_3$=-π, $\dot{\theta}_4$=-$\frac{1}{2}\pi$

in example 3 (fig. 15) a significant shift of the elements into the direction of the rotation axis can be seen (ellipses 1 to 3). In particular free areas have been closed where the force is applied to the structure (ellipses 4 and 5). Thus, this result seems more regular in its shape than the basic model.

The design proposal based on the extended topology optimization (Q_{EDW}) is shown in figure 12. In contrast to the result of the optimization wit Q_{RED} this result is more like the one of the classical topology optimization. So there are more FE shifted to the rotational axis (ellipse 1). Near the areas where the force is applied to the structure (ellipse 2 and 3) the beam is separated into two small beams.

The sum of the kinetic energy of each finite element was calculated by using the element density and volume. Finally the total energy of the design proposal was summed. In the following table 1 the total kinetic energies of the design proposals are compared to the reference model (example 3).

Table 1: kinetic energy for example 1

example	kinetic energy [J]	difference [%]
3	15811	
1 (Q_{RED})	14852	-6.06
1 (Q_{EDW})	15662	-0.94

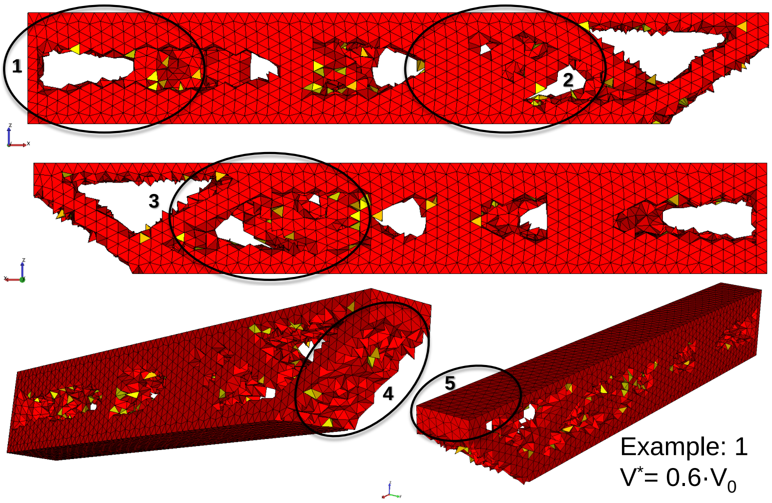

Figure 11: Result for the academic example (example 1 (Q_{RED}))

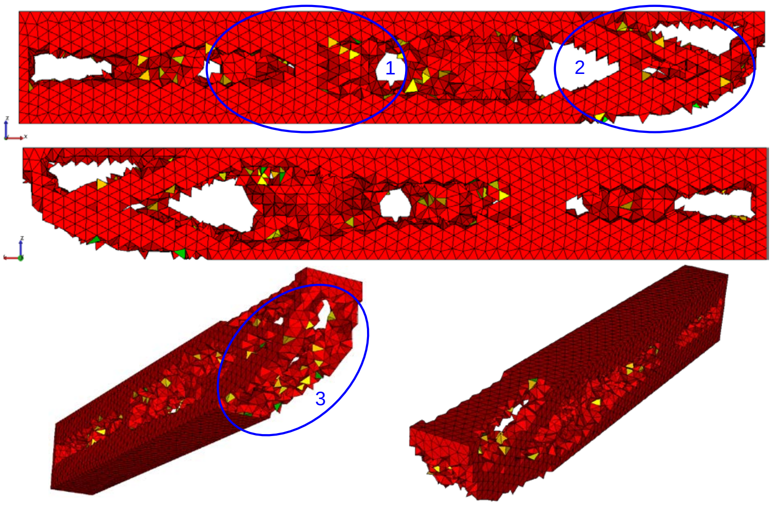

Figure 12: Result for the academic example (example 1 (Q_{EDW}))

Example 2:

The second example is based on the movement of the multi-body system which was introduced before. The kinematic is similar to the kinematics of a humanoid and also industrial robot. The calculated design proposals are therefore from a more realistic topology optimization compared to a traditionally topology optimization, which is based on the energy efficiency of the considered design area. The individual rotational axes of the respective simulation times are relatively far away from the body compared to the first example. In this optimization result (fig. 13) it is noticeable that the optimization algorithm has removed many finite elements in the center area of the design space (ellipse 2 and 3). In the area where the force is introduced to the structure, many finite elements where removed due to the large distance from the instantaneous axis of rotation and the square relationship between the distance and rotational energy (ellipse 4).

The sum of the kinetic energy of each finite element was calculated by using the element density and volume. Finally the total energy of the design proposal was summed. In the following table 2 the total kinetic energies of the design proposal are compared to the reference model (example 3).

Table 2: kinetic energy for example 2

example	kinetic energy [J]	difference [%]
3	8292	
2 (Q_{RED})	8241	-0.61
2 (Q_{EDW})	8279	-0.15

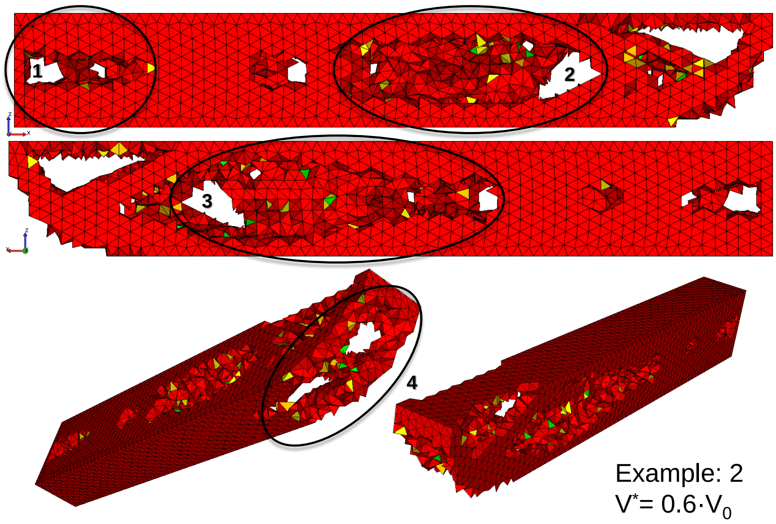

Figure 13: Result for the example with a complex motion (example 2 (Q_{RED}))

Example 3:

This topology optimization result (fig 15) is used as a reference to be able to compare the results from example 1 and 2. It is based on a standard topology optimization.

6 DISCUSSION AND CONCLUSION

In this paper a new optimization process for topology optimization of structural parts, to increase the energy efficiency, has been presented. The classical topology optimization was extended where at different analysis domains, the multi-body system dynamics, finite element analysis and topology optimization are integrated into a straightforward, automatic optimization process. Here, two different trajectories, one academic and one realistic, of mechanical structures in space were taken into account to get a design proposal for a lightweight design for dynamic (accelerated) systems. Using a multi-body system of a robot arm (4 DoF) the energy consumption of the mechanical structure and the descriptive criterion were calculated.

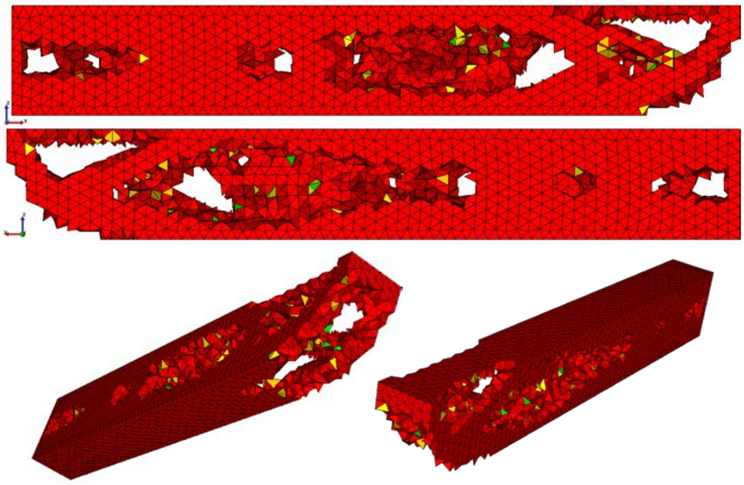

Figure 14: Result for the example with a complex motion (example 2 (Q_{EDW}))

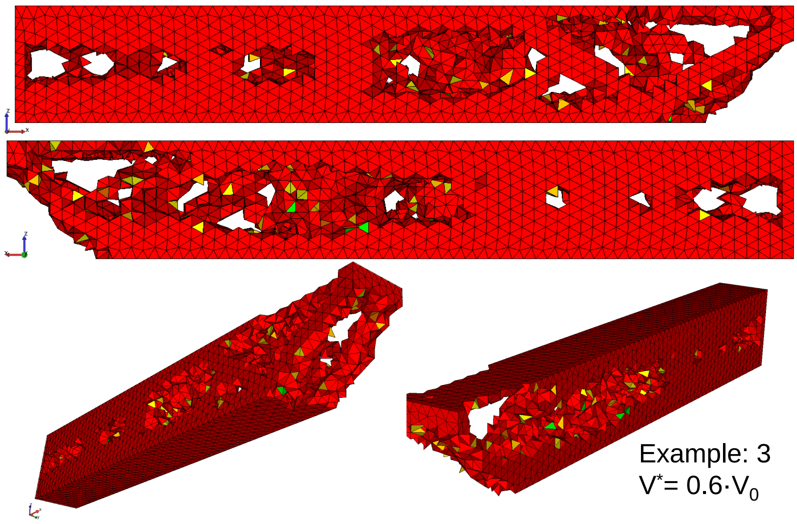

Figure 15: Result for the standard example (example 3)

In this contribution it was shown that, depending on the movement and on which of the approach is used, the developed algorithm is capable to increase the energy efficiency of a mechanical structure by reducing the energy consumption. A reduction of up to 6% of the kinetic energy for moving the part in different trajectories, compared to a traditionally optimized part with the same mass, can be achieved by a different specialized material distribution.

In the future the new optimization process will be applied to more complex models and scenarios. Additionally the main load cases from the dynamic movement have to be calculated automatically in a new extended optimization process.

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