DESIGN FOR ENERGY EFFICIENCY: NEW STRUCTURAL OPTIMIZATION PROCESS FOR A ROBOT SHIFTER

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Abstract

In consideration of limited resources and the steadily increasing population, lightweight design is discussed as one of the possible solutions to improve energy efficiency before a sustainable alternative energy source is developed.

The aim of this study is using a new extended topology optimization process presented in [1], [2] to reduce the inertia and the power consumption of actuators of a robot shifter. To achieve the aim, integrated methods of finite element, multi-body simulation and topology optimization were used for structural optimization. At IPEK – Institute of Product Engineering a new robot shifter was developed for a powertrain in the loop test field. A robot shifter performs automatic shifting operation during the switching cycle in a test stand for gearboxes. As a result of the objectives for this new robot a parallel kinematic was chosen for the horizontal movement. The study presented in this paper verifies the test results of the developed topology optimization process for mechanical loaded parts in dynamic systems with the robot shifter. Within this process, the finite element analysis, the simulation of multibody systems and topology optimization techniques are considered together. Through the integration of different simulation methods, the interactions between components and systems can be considered during structural optimization. A reduction of up to 10% of the kinetic energy for moving the part in different trajectories, compared to the original part with the same mass, can be achieved by a different specialized material distribution. And a new design was proposed based on the results.

This study identifies innovative approaches of structural optimization processes. The design of the individual structure considers the complex system behavior, and enhances the reliability and energy efficiency. This optimization process has been successfully applied to a real world system and will hopefully be used in problems that are more practical in the future.

Introduction

Global energy usage has grown by the factor of 26.5 per capita over the past 200 years [3]. With increasing concerns over this excessive consumption of energy, new methods must be developed to reduce greenhouse gas emissions and to stop climate change. The highest impact in emission reduction contributions can be achieved by increasing the energy efficiency [3]. Therefore, the European Union, several non-governmental organizations and the economy have set the goal to significantly increase the efficiency of the used resources in areas, such as lifestyle, transportation, energy production and industry within the next years [4].

The scientific challenge for product development is to create new methods and to define new processes to be able to find hidden potential for resources and energy savings in technical systems in the future. To achieve this goal, it is inevitable to simulate the functioning technical system and to be able to optimize it.

In the system-based structural optimization the best possible structure of a part can be designed by taking the overall behavior of the system and the interactions of system elements into account. Computer-aided topology optimization is an important method to calculate design proposals for certain boundary conditions and in a given design space. Usually these methods have the goal to find a stiff and lightweight structure without taking the energy efficiency of the system directly into account. These design proposals are typically 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 kinematics of a spatially active multi-body system, it is useful to adapt the material distribution of one part to avoid large moments of inertia that reduce the energy efficiency of this part during dynamic movements.

In this paper the extension of classical topology optimization presented at NAFEMS [1], [2] is shown and applied to the real world system of a robot shifter [5] to reduce the power consumption and therewith to increase energy efficiency of this mechatronic system.

State of Research

The usage of computer aided simulation tools is common practice in product development today. A widely used tool to analyze stress and strain in mechanics is the finite element analysis (FEA) for example. To investigate the dynamic behavior of mechanical systems, multi-body simulations (MBS) are used. An integration of elastic bodies led to more realistic MBS and information about loads exerting on bodies for structural analysis and optimization. Additionally, structural optimization methods have an growing acceptance in modern product development. Topology optimization 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 [6], [7]. By integrating MBS into structural optimization processes, mechanical parts in mechanical systems can be optimized regarding the interaction between the parts mechanical properties and the overall system dynamics [8–10].

In [11] an optimization process for topology optimization of flexible bodies in controlled dynamic mechatronic systems is discussed. It was even extended to an integrated topology optimization method where the control parameters were also optimized during the whole process [12]. In [1] a new approach is presented, discussing an extended topology optimization process which is able to reduce the amount of rotational kinetic energy of an accelerated part. This process was extended [2] to take the load cases in account which are a result of the mass inertia.

[13] present an analytic method for input torques minimization of two degrees of freedom serial manipulators. First, an optimal trajectory is calculated to minimize energy consumption of the manipulator. In a second step the movable masses are redistributed using
an adaptive counterweight 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 robot arm. [14] discuss the architecture optimization of a three-degree-of-freedom translational parallel mechanism designed for machining applications. In their paper they develop a new kinematic structure to meet their requirements, but they are not optimizing the support structure of each robot arm.

In a contribution by Scientists of Chemnitz University of Technology and of Fraunhofer Institute for Machine Tools and Forming Technology 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. [15] For structural optimization they didn’t use an extended topology optimization considering the dynamic behavior to reduce the energy efficiency. Otherwise this additionally should have increased their total energy reduction.

Extended Topology Optimization - Integrated approach for optimization based on energy efficiency

To increase the energy efficiency, the new method has to be capable of automatically reducing the energy consumed by the mechanical structure during a dynamic movement without limiting the functionality. In this context energy is understood to be the potential and kinetic energy stored in the part. The influence of the gravity can be controlled by path planning algorithms and the architecture of the kinematic structure which is common in robotics today [14], [16]. Furthermore the reduction of the potential energy can be achieved using the methods of a classical topology optimization to reduce the compliance and the overall mass.

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, which can affect the kinetic energy of a body. On the one hand, it is the total mass \( M \) of the target structure and on the other it is the material distribution in the rotation, which is expressed in terms of the inertia tensor \( J \). Now, it can be deduced that the energy efficiency of a dynamic moving mechanical structure can only be increased, when its mass is reduced and its material distribution is optimized. The influence of the material distribution in the context of a dynamic movement is the inertia. The inertia of part can be optimized and leads to a reduction of the rotational kinetic energy. A new topology optimization method was developed considering this idea [1], [2].

Example and Results

Model setup

The new optimization process introduced in this study has been applied to the robot shifter (see Figure 1) which is developed for the powertrain-in-the-loop test stand at IPEK - Institute of Product Engineering [5]. The aim of this study is extending the traditional topology optimization process to reduce the inertia and the power consumption of the motors and a design proposal is calculated.

Since the whole structure of the robot shifter is symmetric, only half of the system needs to be analyzed. In order to reduce the simulation time, complex geometric components are replaced by primitives with the same mass and inertia or directly omitted and replaced by an equivalent mass (see Figure 2). In this study the two arms are modeled as flexible bodies which are considered as the design area respectively.

The material properties of the rigid bodies are defined as ferrite steel with \( \rho = 7.85 \times 10^{-9} \mathrm{t/mm}^3 \). The outer contour of the original design area corresponds to the model designed and built for the robot shifter. But it was filled with material for the topology optimization. The material is defined as an aluminum-alloy with \( \rho = 2.7 \times 10^{-9} \mathrm{t/mm}^3 \), a Young's modulus of 70,000 N/mm² and the Poisson’s number of 0.3. The mass maintain the same mass as the model of the built one for comparison. As in Figure 1 illustrated, there are several components at the force measurement side of the robot shifter (end-effector). In order to simplify the structure, the assembly was replaced by one part. However, in the simulation, the gravity forces of these parts must be considered. The mass of these structures are automatically analyzed by the CAD model of the robot. The total mass is about 823 g. At this position in the negative z-direction an equivalent force of 8.23 N will be loaded to instead of gravity. From the specification of the robot the maximum load and angular velocities of the joints can be defined to 500 N and 14.5 rad/s. The direction of the load \( F \) is mainly at an angle of 45° along the negative y-axis and negative x-direction. In this case the two angular velocities \( \omega_1 \) and \( \omega_2 \) also be kept the same in each simulation and directions were shown as in Figure 2.

According to the data used for simulating, the maximum shift rate of the robotic arm is 50 mm. If the angular velocity is set to 14.5 rad/s, the run time of simulation is 0.03 s. To show the effects of the dynamic load case determination and the adaption coefficient used in the new optimization approach, the model was simulated in three different ways with an optimization volume constraint of 60%.

1) A new extended topology optimization (DyTopKE) with a dynamic load case determination and a dynamic calculation of the adaption coefficient for decreasing the kinetic energy was used to calculate a design proposal.

2) An extended topology optimization (DyTop) was conducted in which the load cases were determined in every step of the topology optimization and updated for every iteration without taking the kinetic energy of any finite element into account.

3) A traditional topology optimization with two static load cases was used to calculate a design proposal.

The design areas are meshed with 79,988 linear tetrahedral elements (CTETRA4) for the upper arm and 79,081 linear tetrahedral elements for forearm to get a satisfactory stress prediction. In order to keep intact connections of the multi-body system, the elements near
to the joints must be defined as "Frozen" (see white area in Figure 3) and thus be removed from the design area during the simulation time. In the following the results of these three types of optimization are shown and studied regarding differences.

Figure 3: The design area with "Frozen" elements for the upper arm and forearm

Results
In this subsection the results for the two parts are discussed with three different approaches. The design proposal, the energy efficiency and the maximum displacement are compared.

Segment a: upper arm - comparison of the design proposal
The different design proposals of the upper arm from the extended topology optimization compared to the traditionally topology optimization are shown in Figure 4. The load cases in the simulation are not directly applied to the upper arm, but the interaction of the multi-body system affects this behavior. In these optimization results (Figure 4) it is noticeable that the traditional topology optimization algorithm has removed many finite elements in the area near the forearm (ellipse 1). Especially the structure in this area was reduced to a bigger typical framework. At the same time elements at the bottom side were removed (ellipse 2). In contrast, the extended topology optimization algorithm has removed more elements along the edge of the structure, especially stronger on the bottom side (ellipse 3).

Figure 4: Comparison with design proposal for upper arm

Table 1 shows the difference in energy consumption and the maximum displacements of the different design proposals for the upper arm. The power and kinetic energy were calculated during the final simulation iteration of the design proposal. Compared to the reference model (example a2) about 11% of the kinetic energy is more consumed by the original structure (example a3). In contrast, almost 1% of the kinetic energy can be saved with the model from the extended topology optimization (DyTopKE). Although compared to the original structure (example a3), the design proposal with the model (example a1) from the extended topology optimization produces a relatively smaller maximum displacement, but the minimum displacement was generated by reference model (example a2).

Table 1: Kinetic energy and maximum displacement for upper arm

<table>
<thead>
<tr>
<th>example</th>
<th>Δ energy [%]</th>
<th>maximum displacement [mm]</th>
<th>Δ displacement [%]</th>
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<tbody>
<tr>
<td>A3 Original Geometry</td>
<td>10.96</td>
<td>0.4686</td>
<td>26.41</td>
</tr>
<tr>
<td>A2 Extended Topology Optimization (DyTop)</td>
<td>0</td>
<td>0.3707</td>
<td>0</td>
</tr>
<tr>
<td>A1 Extended Topology Optimization (DyTopKE)</td>
<td>-1.01</td>
<td>0.3942</td>
<td>6.34</td>
</tr>
</tbody>
</table>

Segment b: forearm - comparison of the design proposal:
The different design proposals of the forearm are shown in Figure 5 and from the extended topology optimization compared to the traditional topology optimization. The load cases of the simulation times are directly applied to this forearm on the right side. Therefore in these optimization results (Figure 5) it is noticeable that both topology optimization algorithms have removed many finite elements in the area where the forces are introduced to the arm. Especially the structure in this area was stronger reduced by the extended topology optimization algorithm (ellipse 2 and 3). At the same time elements at the bottom side were removed more than at the upper side. Furthermore the extended topology optimization algorithm has removed more elements in the center of the structure on the upper side (ellipse 1).
Table 2 shows the difference in energy consumption and the maximum displacements of the different design proposals for forearm. The power and kinetic energy were also calculated during the final simulation. The differences are compared to the reference model (example b2).

Compared to the reference model (example b2) about 3% of the kinetic energy is more consumed by the original structure (example b3). In contrast, almost 2% of the kinetic energy can be saved with the model from the extended topology optimization. The results of the maximum displacement are comparable to the results above. Although compared to the original structure (example b3), the design proposal with the model (example b1) from the extended topology optimization produces a relatively smaller maximum displacement, but the minimum displacement was generated by model b2.

Table 2: Kinetic energy and maximum displacement for forearm

<table>
<thead>
<tr>
<th>example</th>
<th>Δ energy [%]</th>
<th>maximum displacement [mm]</th>
<th>Δ displacement [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B3 Original Geometry</td>
<td>3.16</td>
<td>0.1718</td>
<td>6.25</td>
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<tr>
<td>B2 Extended Topology Optimization (DyTop)</td>
<td>0</td>
<td>0.1617</td>
<td>0</td>
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<tr>
<td>B1 Extended Topology Optimization (DyTopKE)</td>
<td>-2.01</td>
<td>0.1642</td>
<td>1.55</td>
</tr>
</tbody>
</table>

Discussion and Conclusion

In this paper an optimization approach for topology optimization of structural parts in dynamic systems has been presented and been used to optimize IPEKs robot shifter. The multi-body system dynamics, finite element analysis and topology optimization are integrated into a straightforward, automatic optimization process. Here, one trajectory of two mechanical structures of the robot shifter were considered to calculate a design proposal for an improved lightweight design. The energy of the mechanical structure and a descriptive criterion were calculated. Six different examples were compared. A reduction of up to 10% of the kinetic energy for moving the design proposal, compared to the original structure with the same mass and outer geometry, can be achieved by a different specialized material distribution, although the maximum displacement was reduced at the same time.

In this paper it was shown that, depending on the approach used, the developed method is capable to increase the energy efficiency of a mechanical structure. In the future the developed optimization process will be applied to more complex models and scenarios. Additionally the sensitivity-based optimization algorithm will be used to improve this developed optimization process.

References


