Towards Large-Scale Topology Optimization of Dynamically Loaded Components of Flexible Multibody Systems

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Energy efficiency is a permanent issue in modern engineering. For instance, in a multibody system, one important aspect to reduce the energy consumption is the utilization of lightweight component design. Thus, moving masses can be reduced and the mass to payload ratio is improved. However, as a result the stiffness of the bodies decreases and non-negligible structural deformations might appear during the working motion. As a consequence such multibody systems must be considered as flexible. Then, structural optimization methods can be used to design lightweight components of the flexible system such that minimal undesired oscillations occur during working motion. In order to capture in the optimization the correct dynamic loading on the components, simulations of flexible multibody systems are coupled with structural optimization for the flexible components of the system.

In this research, topology optimization is used, which is a powerful tool for designing lightweight structures. This method tries to find the best distribution of material in a fixed design space where any formation of material inside the specified domain is allowed. In the past, engineering application of topology optimization has been limited since the obtained designs are often hard to manufacture with traditional methods. However, with the emerging additive manufacturing techniques, these limitations become less relevant and many new application fields for topology optimization arise.

Topology optimization is mostly based on a finite element discretization of the design domain. Then, to each element, a design variables x_i is assigned. The design variable corresponds to the degree of filling of the element, where only $x_i = 0$ (empty) or $x_i = 1$ (filled) are physically meaningful. Such a $0-1$ design is desired, however, due to its discrete nature, it is not practical to solve. Therefore, this discrete optimization problem is transformed into a continuous optimization problem using the solid isotropic material with penalization (SIMP) approach, see [1]. Traditionally topology optimization is mostly performed for minimizing compliance under static loading. Lately, large-scale implementations of such static optimization problems with millions of design variables are presented [2].

Parallel to static problems, there has recently been extensive research on topology optimization of flexible multibody systems. In this work, the floating frame of reference approach is used, whereby the SIMP parameterized finite element model is included using component mode synthesis [3]. The basic approach for topology optimization of components of flexible multibody systems is using a weak coupling of the flexible multibody simulation and the topology optimization by means of equivalent static loads [4, 5]. Thereby, the dynamic loads on the flexible bodies are considered in the optimization only at selected time points. Moreover, these loads are assumed to be design and time independent. In the topology optimization of flexible multibody systems, a challenging task is the sensitivity analysis of the objective function with respect to the design variables. This is especially expensive since the number of design variables in topology optimization is normally very high. Using the weakly coupling approach, the sensitivity analysis can be performed similar to static problems. However, this formulation provides only an approximation of the gradients, since the dependency of the loads on the design variables is neglected. This has been shown to be a major drawback if dynamical forces are the dominant loads on the optimized bodies. In this case, no meaningful optimized design can be found [6]. In [7] it is shown, that such a weakly coupled approach can be adjusted to account for some of these dynamical forces with little additional computational cost. This can improve the gradient computation significantly, and meaningful designs can be obtained even if the dynamic loading originates from the optimized component's inertia. Due to the transformation to a quasi-static problem, such a weakly coupled approach allows large-scale topology optimization problems for components of flexible multibody systems. However, even in the adjusted case, one still uses only an approximated gradient.

Alternatively, it is possible to calculate the exact gradients of the objective function in a flexible multibody system, using for instance the adjoint variable method, see [6]. In this fully coupled approach, all the dependencies of the objective function and the system dynamics on the design variables are considered, hence, the optimization is able to converge to a solution even when the loads are highly design-dependent. However, this is a very time consuming approach. As a result, so far, the size of dynamic topology optimization problems using exact gradients has been strongly limited to several hundreds or few thousand design variables.

This talk addresses therefore the efficient and fast gradient computation for dynamic systems with a high number of design variables which is the case in topology optimization of flexible multibody systems. In a first step, the automatic detection and elimination of negligibly small derivation terms is introduced. This increases the computational efficiency without deteriorating the accuracy of the gradients. In a second step, the parallelization of the gradient computation is presented. Both improvement steps are tested in the topology optimization of a flexible three-dimensional slider-crank mechanism. With the introduced elimination of negligible terms in the gradients and the parallelization of gradient computation, it is shown that the gradient computation, and thus the topology optimization, can be carried out in a feasible time with respect to more than 100.000 design variables.

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