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ScienceDirect
Comput. Methods Appl. Mech. Engrg. 329 (2018) 312–331
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

System-wise equivalent static loads for the design of flexible mechanisms

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Received 16 June 2017; received in revised form 28 September 2017; accepted 1 October 2017
Available online 19 October 2017

Highlights

- System-wise equivalent static loads (ESL) are defined for mechanism design.
- Global displacements of the mechanism are naturally included in the optimization problem formulation.
- The generality of the resulting static response optimization problem is extended.
- System-wise ESLs are detailed for a particular Lie group nonlinear finite element formalism.
- Properties of the adopted formalism are exemplified for three mechanism designs.

Abstract

Structural optimization of flexible multibody systems (MBS) is a challenging design problem which has received increased attention in the last decade. The weakly coupled method is a powerful method to solve this design problem as it transforms the underlying dynamic response optimization problem into a static response optimization problem subject to multiple load cases. These load cases can be conveniently defined using the so-called Equivalent Static Load (ESL) method. With the usual ESL method, ESLs are defined at a component-level assuming that each component is isolated from the rest of the system. Thus, this method cannot account for design functions involving the global response of the system but it is restricted to optimization problems that are solely formulated in terms of local responses within the components. In order to get rid of this restriction, a system-wise extension of the ESL method is proposed. It is shown that the solutions of the equivalent static optimization problem and of the initial MBS optimization problem are equivalent and that the ESL formulation naturally leads to a weakly coupled solution algorithm. Standard benchmarks exemplify the proposed method.
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Keywords: Structural optimization; Flexible multibody systems; Weakly coupled method; Equivalent static load (ESL); Nonlinear finite element method; Local frame formalism (SE(3))

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https://doi.org/10.1016/j.cma.2017.10.003
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1. Introduction

1.1. State of the art

The optimal design of mechanical system components usually relies on a component-based approach wherein standard methods of static response optimization are applied. In this approach, the optimized components are isolated from the system and subjected to boundary and loading conditions to predict deformations, stress distributions, etc. These boundary and loading conditions generally come from the designer experience, empirical relations or experimental efforts. Although the majority of loads are dynamic, structural optimization is then typically performed under (quasi-)static or frequency domain loadings, thereby avoiding the difficulties of evaluating the dynamic response and incorporating it in the optimization.

With the evolution of multibody system (MBS) analysis, the component-based approach has been extended to a system-based approach. The latter captures the system behavior by employing a MBS simulation that evaluates the response of the whole system. Bruns and Tortorelli [1] were amongst the first to propose such an approach by combining rigid MBS analysis and optimization techniques. To perform the optimization, they extracted some load cases evaluated during the MBS analysis. Later on, Oral and Kemal Ider [2] proposed a methodology to consider the coupled rigid-elastic motion of MBS system within the optimization loop and they incorporated time-dependent constraints in the optimization problem. This holistic approach is essential since the optimal design may be very sensitive to the support and loading conditions.

Adopting the system-based approach to conduct optimization of mechanical systems, two optimization methods can currently be identified: the weakly coupled and the fully coupled methods [3]. The fully coupled method solves a dynamic response optimization problem which incorporates the time response coming directly from the MBS simulation. Hence, this method naturally accounts for the system global response and dynamic effects. The exact sensitivities of the MBS time response can be evaluated and exploited for a fast convergence of the optimization algorithm in the vicinity of the optimal design. However, the formulation of the MBS optimization problem should be carefully addressed as it significantly impacts the optimal solution and also the convergence of the optimization process [4]. In particular, the treatment of time-dependent responses is rather complex and the influence of the changes of component inertial property on vibrations and the interactions between flexible components generally result in complex design problems. Nonetheless, even if the optimization process may be arduous, the fully coupled method is totally general to design optimal mechanisms and has been employed in numerous works, for instance [5–9].

Instead of solving a dynamic response optimization problem, the weakly coupled method reformulates the design problem in a two-step approach. Firstly, a MBS simulation predicts the dynamic loading applied to the system and secondly, a quasi-static approach is adopted to solve the design problem. In this second step, the Equivalent Static Load (ESL) method has become the reference method to define a series of static load cases mimicking the dynamic loading in a rational manner. Even though ESLs are design-dependent, the static response optimization process considers them as constant, i.e. design-independent. Consequently, cycles between MBS analysis and optimization process are required to factor in the effect of mass redistribution over the load cases. Compared to the fully coupled method, it is however not necessary to evaluate the sensitivity of the MBS dynamic response, which is a significant advantage. The weakly coupled method has been used in various works, for instance [10–16].

1.2. Motivations for the present work

The Equivalent Static Load method is the cornerstone of the weakly coupled method. Indeed, the ESL method defines equivalent static load cases rationally whereupon the dynamic response optimization problem can be transformed into an equivalent static response optimization problem. The latter is then efficiently solved using standard techniques of structural optimization.

The ESL method was first introduced by Choi and Park [17,18] to perform structural optimization of a single structure (not mechanism) subject to dynamic loading. The main motivations of developing such a method were to avoid the expensive computation of state variable derivatives, the possibility of using efficient commercial solvers for structural optimization of the static response and to circumvent the difficult treatment of time-dependent constraints.

Kang *et al.* [10] extended the ESL method to optimize mechanical systems modeled using a floating frame of reference formulation. This MBS formalism is well-suited to derive ESLs as originally proposed by Choi and Park for a structure [19,20]. Indeed, this MBS formalism describes the flexibility of each component in a body-attached

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