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*Editorial*

# Modeling, Design and Optimization of Flexible Mechanical Systems

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## 1. Modeling, Design and Optimization of Flexible Mechanical Systems

Performance, efficiency and economy drive the design of mechanical systems and structures and has led lightweight engineering design to prominence. This push for economy of material use inherently leads to more flexibility in the components of mechanical systems, both with its opportunities and challenges. Three general categories of research contributions were identified for flexible mechanical systems in this Special Issue: design, modeling, and optimization. These will be introduced in the following.

### 1.1. Design

The consideration of flexibility leads to new engineering design paradigms. Flexibility can be seen both in positive and negative light; i.e., where flexibility is a design benefit or where it is a design constraint.

Performance, efficiency and economy are tied together in the Virtuous Circle of Lightweight Engineering Design, introduced in [1]. With less structural mass, the structural requirements, motorization requirements or both are reduced and therefore the structural mass can in turn be reduced again. The Virtuous Circle design philosophy is magnified when looking at dynamic systems in which self-weight is reduced and therefore inertial forces. This philosophy delivers designs to their limit, and therefore will result in designs at the maximum allowable displacement and therefore is inherently connected to flexibility.

In the design of complaint mechanisms, specific flexibility is sought. Compliant mechanisms are a class of mechanisms that utilize elastic deformation instead of hinges. These exhibit a wide range of advantages, as outlined in [2–4], which include their lightweight nature, lack of backlash, as well as increased precision and reliability. Applications include robotic grippers, e.g., [5], morphing aircraft wings, e.g., [6,7], micro-electro-mechanical systems (MEMS), e.g., [8]. The design of such mechanisms is an active research field that has been heightened with the growth of additive manufacturing techniques, e.g., [9].

Lighter, more flexible mechanical systems are also prone to vibration. This must therefore be considered in the design process, not just as an afterthought as often occurs, via passive or active measures. Design formulations include more traditional minimal allowable natural frequencies, designing for a specific natural frequency, e.g., [10], vibration absorption components, e.g., [11], as well as avoiding frequency ranges, e.g., [12]. A concept that has seen recent attention is the harvesting of vibrational energy, e.g., by [13] and reviewed by [14].

Natural motion is a further design philosophy that utilizes a properly designed compliance and accordingly the eigenbehavior (natural frequency and mode shape) to reduce the energy needed to perform cyclic motion, see, e.g., [15,16]. A review and categorization is provided by [17,18]. This field is set to grow in the future to properly design systems that require less energy.

### 1.2. Modeling

Multibody simulation (MBS) models and analyzes the dynamic behavior of mechanical systems, especially those with kinematic constraints. Research is active in the formulation of flexible multibody dynamics, which are reviewed in [19–21]. Flexible multibody formulations include floating frame of reference formulation (FFRF) by [22], absolute nodal coordinate formulation (ANCF) by [23], absolute coordinate formulation (ACF) by [24], equivalent rigid link system (ERLS) by [25–27] and further developed by [28,29]. With further refinement, proper application and use in optimization (see below), MBS will continue to see attention.

With ever more flexibility, linear-elastic finite-element analysis is not able to properly model large deformations, rotations and strains, even if the material remains in the elastic domain. This requires the use of geometrically nonlinear finite-element analysis with its application and developments, e.g., [30].

### 1.3. Optimization

Design optimization is an effective method that finds a design which minimizes (or maximizes) a performance criteria (objective), while fulfilling predefined design constraints, see [31–33]. The design is defined by design variables, which can include geometrical properties (size, shape and topology), material, concept and operational parameters. The synthesis of flexible mechanical systems can be aided by numerical optimization, in the search for improved designs.

Design optimization of multibody dynamics presents challenges in regard to, i.a., sensitivity analysis, high computational effort and transient behavior. Design optimization of rigid multibody systems is handled by [34–37], while the optimization of flexible multibody dynamics is currently an active research field and reviewed in [38].

Topology optimization answers the question of where material should be optimally placed, and a method to design compliant mechanisms was introduced by [39,40]. Topology optimization of compliant mechanisms is reviewed in [41]. Active research includes consideration of nonlinear finite-element analysis, stress constraints, e.g., [42–44], material choice, e.g., [45], and extension to large-scale problems, e.g., [46].

## 2. Special Issue

This Special Issue offers a platform for the dissemination of the newest research to flexible mechanical systems in an open-access format. The call for papers in the special issue *Modeling, design and optimization of flexible mechanical systems* in *Applied Science* was open from 1 January 2020 to 31 March 2021 and received 26 manuscripts, 13 of which were selected to be published, giving a 50% approval rate. These manuscripts cover the wide range of the topics introduced above and are listed here in order of publication.

Wu et al. [47] *Dynamic analysis of spatial truss structures including sliding joint based on the geometrically exact beam theory and isogeometric analysis* introduces a NURBS-based isogeometric analysis for flexible multibody simulation and applies this to a high-speed flexible slider-crank, a sliding beam, and a spatial truss structure.

Liu et al. [48] *Kinematic modelling and experimental validation of a foldable pneumatic soft manipulator* develops and validates a numerical model with respect to shape deformation.

Noveanu et al. [49] *SiMFlex micromanipulation cell with modular structure* proposes a high-precision complaint gripper concept including finite-element analysis and experimental investigations.

Zeng et al. [50] *Dynamic behaviour of a conveyor belt considering non-uniform bulk material distribution for speed control* develops and experimentally verifies a high-precision longitudinal model to analyze dynamic behavior.

Boxberger et al. [51] *Development of everting tubular net structures using simulation for growing structures* demonstrates the use of resin to design a highly flexible structure based on analysis with non-linear finite-element analysis. The additively manufactured structure can be repeatedly everted, i.e., turned inside out, without failure.

Han et al. [52] *Iterative coordinate reduction algorithm of flexible multibody dynamics using a posteriori eigenvalue error estimation* introduces a method allowing the engineer to choose the allowable error when using model-order reduction.

Palomba et al. [53] *Minimization of the energy consumption in industrial robots through regenerative drives and optimally designed compliant elements* presents a method to retrofit mechanical systems to recover and store energy based on numerical simulation and an optimization routine.

Kim et al. [54] *Experimental and numerical investigation of solar panels deployment with tape spring hinges having nonlinear hysteresis with friction compensation* develops an experimental test and implements a multibody analysis.

Liu et al. [55] *Simulation analysis and experimental verification of the locking torque of the microgravity platform of the Chinese space station* considers the vibrational load of launch using simulation and experimental investigations.

Richiedei and Tamellin [56] *Active approaches to vibration absorption through antiresonance assignment: A comparative study* reviews and contrasts methods for the assignment of resonance frequencies and mode shapes.

Reinisch et al. [57] *Multiresolution topology optimization of large-deformation path-generation compliant mechanisms with stress constraints* introduces a methodology for the design of compliant mechanisms based on non-linear finite-element analysis.

Goubej et al. [58] *Employing finite element analysis and robust control concepts in mechatronic system design-flexible manipulator case study* analytically and numerically models a flexible benchmark for vibrational analysis, system identification and robust control.

Ge and Kou [59] *Topology optimization of multi-materials compliant mechanisms* utilizes a SIMP-based approach to the design of compliant mechanisms of multiple materials with application to standard benchmarks of the topology optimization community.

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