Topology Optimization of Bearing Domains in Flexible Multibody Systems

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Abstract

Topology optimization has been successfully applied to optimize members of flexible multibody systems. For instance, using the floating frame of reference approach, topology optimization procedures have been proposed and tested by [1, 2, 3]. In this formulation, the linear deformation of an elastic body in a multibody system is described with respect to a body-related frame and the large rigid body motions are described by the non-linear motion of this frame. Therewith, the position vector of a point on the flexible body is determined by the sum of rigid motion and the linear deformation $\mathbf{u}_\mathrm{P}$. The deformation $\mathbf{u}_\mathrm{P}$ is approximated by a time-independent matrix of shape functions $\mathbf{\Phi}$ and time-dependent elastic coordinates $\mathbf{q}$ as

$$\mathbf{u}_\mathrm{P}(\mathbf{R}_\mathrm{P},t) = \mathbf{\Phi}(\mathbf{R}_\mathrm{P})\mathbf{q}(t) \tag{1}$$

where $\mathbf{R}_\mathrm{P}$ is the position vector in the body-related frame. Writing the equations of motion in minimal coordinates, as explained in [7] and rearranging them, a time-variant equivalent force $\mathbf{f}_\mathrm{eq}$ is obtained which includes all the dynamic loads applied to the flexible bodies

$$\mathbf{K}_\mathrm{ee}\mathbf{q}(t) = \mathbf{f}_\mathrm{eq}(t). \tag{2}$$

Thereby, $\mathbf{K}_\mathrm{ee}$ is the stiffness matrix of the generalized elastic coordinates. Equation (2) can be solved for a finite number of time points to obtain a set of deformation fields

$$\mathbf{u}_i = \mathbf{\Phi}(\mathbf{R}_\mathrm{P})\mathbf{q}_{t_i} = \mathbf{\Phi}(\mathbf{R}_\mathrm{P})\mathbf{K}_\mathrm{ee}^{-1}\mathbf{f}_{\mathrm{eq},t_i}, \quad i = 1,2,...,m. \tag{3}$$

Here, t_i is the i-th time point and m is the total number of load cases.
In the integration of flexible bodies in a multibody system it is necessary to model the interfaces with other connected bodies. In the previous studies [2, 3], due to the simplicity of implementation, the flexible body is connected to the interface nodes by means of truss elements or rigid elements. In this approach, the joint area is considered as ground structure, i.e. excluded from the optimization. However, using this joint model, no information will be provided regarding the optimized shape of joints. In addition, inclusion of joints in the optimization domain affects the rest of the structure. This influence is noticeable in Figure 1 and Figure 2 where adding the flexible joint has changed the optimized design in the rest of the structure.
Therefore, accurate modeling of joints is not only important for knowing the optimal design of joint area, but also for increasing the accuracy of the optimized structure in general. This generates a strong motivation for examination of joints in topology optimization of a multibody system where joints as the connecting elements between bodies of the system are intrinsically ubiquitous.
A simple ideal revolute joint is implemented in the optimization of flexible multibody systems, presented in [4]. Here, linear truss elements are used to model the revolute joints in the topology optimization of a slider-crank mechanism. For an ideal joint it is assumed that there are no clearance and no relative sliding between the journal and the bearing. The ideal model allows the use of model order reduction techniques

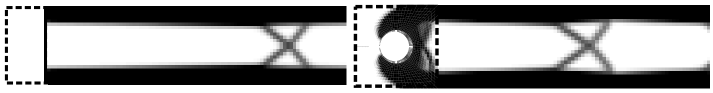

Figure 1: Optimized structures with rigid interface area (left) and rigid bearing (right)

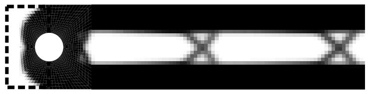

Figure 2: Optimized structure using flexible joint.

which facilitates the dynamic simulation of the slider-crank mechanism with flexible bodies. However, the ideal model fails to represent the exact behavior of revolute joint in the presence of clearance between the moving parts. This is shown in Figure 1 where an unrealistic solution is generated by the optimization in which the ideal joint model is used. The assumption that the clearance is zero and that no sliding occurs between the two contact surfaces, enables the structure to be connected to the journal through one or multiple separated surfaces. Moreover, studies on the dynamics of multibody systems with joints show that the contact forces in the real joints are considerably higher than the ones predicted by ideal joints, see [5, 6].

In the simulation procedure explained in Equations (1-3) it is not possible to implement a nonlinear contact model since the approximation of deformation vector in Equation (1) is linear. However, by introducing a corrector load $\mathbf{f}^{\text{cor}}$ in each time step, it is possible to increase the accuracy of the ideal joint model. This additional load is introduced as

$$\mathbf{f}_i^{\text{cor}} = \mathbf{f}_i^{\text{con}} - \mathbf{f}_i^{\text{ideal}} = \mathbf{f}_i^{\text{con}} - \mathbf{K}\bar{\mathbf{u}}_i, \quad i = 1, 2, ..., m. \tag{4}$$

Here, the deformation vector $\bar{\mathbf{u}}_i$ is equal to $\mathbf{u}_i$ at interface degrees of freedom and is 0 elsewhere. The additional joint loads $\mathbf{f}_i^{\text{con}}$ are calculated using the well-known Herz contact law in normal direction and modified Coulomb law [5] in tangential direction. Including the correction loads of Equation (4) in Equation (3) gives the new displacement vectors $\hat{\mathbf{u}}_i$

$$\hat{\mathbf{u}}_i = \mathbf{\Phi}(\mathbf{R}_{\text{P}})\mathbf{K}_{\text{ee}}^{-1}\mathbf{f}_{\text{eq},t_i} + \mathbf{K}^{-1}\mathbf{f}_i^{\text{cor}}, \quad i = 1, 2, ..., m. \tag{5}$$

Thereafter, calculation of objective function which in this work is the compliance of the flexible body is straightforward

$$c = \sum_{i=1}^{m} \hat{\mathbf{u}}_i^{\text{T}}\mathbf{K}\hat{\mathbf{u}}_i. \tag{6}$$

The application examples of a slider-crank mechanism and a two-arm manipulator are used to demonstrate the effects of the correction loads on the accuracy of the joint modeling. Finally, the application examples with modified linear joint model presented in this work are compared with a similar model in ABAQUS where the contact forces are calculated using the penalty method.

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