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Configuration design sensitivity analysis of dynamics for constrained mechanical systems

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Abstract

A continuum-based configuration design sensitivity analysis method is developed for dynamics of multibody systems. The configuration design variables of multibody systems define the shape and orientation changes. The equations of motion are directly differentiated to obtain the governing equations for the design sensitivity. The governing equation of the design sensitivity is formulated as an overdetermined differential algebraic equation and treated as ordinary differential equations on manifolds. The material derivative of a domain functional is performed to obtain the sensitivity due to shape and orientation changes. The configuration design sensitivities of a fly-ball governor system and a spatial four bar mechanism are obtained using the proposed method and are validated against these obtained from the finite difference method.

1. Introduction

Design sensitivity analysis methods for multibody systems have appeared in several pieces of literature [1–4]. There were basically two different approaches. One is the direct differentiation method [1] and the other is the adjoint variable method [5]. The adjoint variable method was employed from the area of optimal control and involves forward numerical integration for dynamic analysis and backward numerical integration for sensitivity analysis. Since backward numerical integration incurs some numerical error and large data storage requirements, the direct differentiation method is used in this paper.

Configuration design sensitivity analysis methods are well developed in the area of the structural mechanics. Sensitivity analyses of the static response and eigenvectors due to configuration design change are presented in [6–12]. Twu and Choi [11] developed a continuum-based configuration design sensitivity analysis method for static responses and eigenvalues, using the material derivative idea developed for shape design sensitivity analysis. Shape and orientation design changes are separated. Two basic assumptions are made throughout the development of the orientation design sensitivity analysis: (1) the design component rotates without shape changes and (2) only a small design perturbation is considered. Line and surface design components are considered. In contrast to the structural design area, research in sensitivity analysis for the mechanical system design area has been limited to relatively simple mechanical systems, since the system responses are highly nonlinear and the design problems have not been well-defined.

Design propagation analysis due to a design change of mechanical systems has been presented in [13], where the size of a rigid body of a mechanical system is perturbed. The design perturbation of one body

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influences the positions and orientations of the rest of the bodies and the state variables are modified to satisfy all kinematic admissibility conditions. However, the modification process may not yield a unique state. To avoid the nonunique state problem, a configuration design change method can be used.

If all points and orientations on a body are taken as design variables, there are too many design variables for a practical design consideration and thus many design constraints must be imposed among these variables to satisfy kinematic admissibility conditions. Therefore, the configuration design change of a body is proposed in this paper. Benefits of the configuration design variable are twofold. First, the number of the design variables will be significantly reduced. Second, the velocity field can be selected so that kinematic admissibility conditions are satisfied, which eliminates the modification process of state variables after a design change. The sensitivity analysis method in [11] was applied for the configuration design sensitivity analysis of kinematic responses in [16]. In this paper, the same theory is then applied to configuration design sensitivity analysis of multibody system dynamics. The kinematics and concept of configuration design changes of a body are introduced in Section 2. Section 3 derives the governing equations of design sensitivity due to a configuration change and a solution method, using an implicit integration method. The numerical examples are presented in Section 4. Finally, conclusions are drawn in Section 4.3.

2. Configuration design change of a body

Consider the rigid body to be designed in Fig. 1. The body is considered as a continuum during a design stage. The x'–y'–z' frame is the body reference frame and the X–Y–Z frame is the inertial reference frame. The design reference frame on which a design is defined must be specified. The body reference frame x'–y'–z' is chosen as the design reference frame in this paper.

Since the body shown in Fig. 1 is considered as a continuum, the location and the orientation of all points on the domain of the body are treated as design parameters to be determined in this paper. Consequently, the point reference frame of the x''–y''–z'' is assigned at all points on the domain. The location design parameter, $\mathbf{s}_0$, and the orientation design parameter, $\boldsymbol{\theta}_0$, of the x''–y''–z'' frame with respect to the design reference frame of the x'–y'–z' frame are treated independently. The orientation design parameter can be parameterized in many different ways and the 3–1–3 Euler angles $(\theta_1, \theta_2, \theta_3)$ [14] are used in this paper. It is assumed that the x''_τ–y''_τ–z''_τ frame remains an orthogonal frame after a design change.

Suppose that only one parameter, τ, defines the transformation $\mathbf{T}_\Omega$, as shown in Fig. 1, where $\boldsymbol{\Omega}_\tau$, $\boldsymbol{\Gamma}_\tau$, and the x''_τ–y''_τ–z''_τ frame denote the changes of $\boldsymbol{\Omega}$, $\boldsymbol{\Gamma}$, and the x''–y''–z'' frame by the mapping $\mathbf{T}_\Omega$, respectively. The mapping

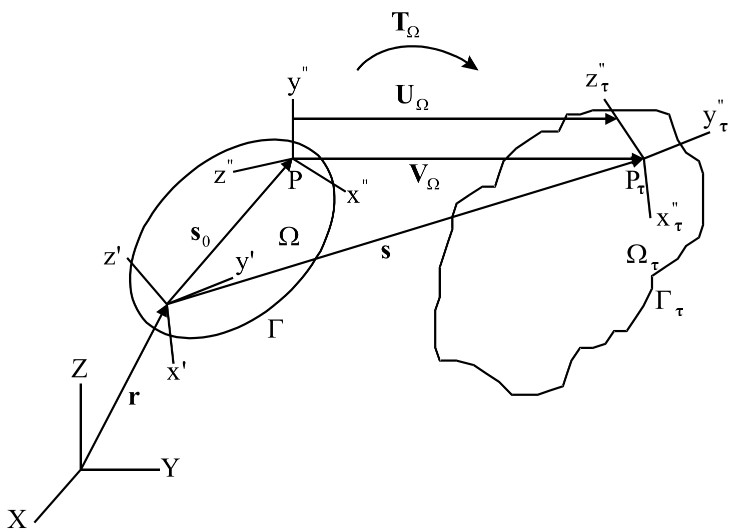

Fig. 1. Configuration change of a body by mapping T.