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Quasi-static consideration of high-frequency modes for more efficient flexible multibody simulations

Abstract A number of sets of modes, for example eigenmodes, constraint modes, inertia-relief attachment modes, may be used to describe the linear elastic deformation of a flexible body in multibody dynamics. It is always possible to transform modes so that the conditions of the Buckens-frame are fulfilled. The latter frame leads to serious simplifications in the equations of motion, but cannot avoid a coupling between the body’s rotational rigid body motion and its elastic deformation. In the present paper the deformation modes will be subdivided into low- and high-frequency modes. It will be shown that the latter-mentioned coupling effect of the second ones can be safely neglected in comparison with the first ones. Consequently, the high-frequency components can be removed from time integration at all, which leads to significant savings of computational effort while the accuracy regarding the body’s deformation remains almost the same. In the case of a known frequency content of external excitation, an algorithm is given so that the available modes can be automatically separated into such low- and high-frequency modes. While the number of low-frequency modes remains more or less constant, there is a significant trend to use an increased number of high-frequency modes. Examples are moving loads (e.g., guidance) or distributed loads as they occur in contact problems or when fluid pressure is acting on surfaces. A final numerical example is given in order to demonstrate the potential of the proposed method.

1 Introduction

The most frequently used approach in multibody simulation to consider body flexibility is the floating frame of reference formulation (FFRF), see [29,34]. The basic idea of this method is the separation of the overall motion of a single flexible body into a nonlinear rigid body motion and a superimposed deformation. In many
A common way to model body flexibility is the finite element (FE) method, see [39]. In order to reduce the number of nodal FE degrees of freedom (DOF) and, thus, to increase computational efficiency, some form of Ritz-vector-based model reduction technique is usually applied. A wide-spread method is the component mode synthesis (CMS). The underlying idea of such methods is that a body’s deformation can be approximated by a linear combination of pre-selected shape functions, which are commonly denoted as modes. Each such mode represents a DOF, and the technical highly relevant assumption that an accurate solution is just needed in a predefined frequency range leads to a significant saving of DOFs in contrast to the nodal approach. For a comprehensive comparison between the nodal and modal approach the interested reader is referred to [11]. In the present paper the focus is only on the modal approach.

Various methods on the selection of the modal shape functions with different characteristics and advantages have been presented during the last decades, see e.g. [10], for a comprehensive review on CMS methods. In the majority of cases, the set of shape functions is composed of global vibration modes (eigenvectors of the structure) and static displacement fields (constraint modes [8,16] and attachment modes [9,21,24]). While global vibration modes are needed to capture the desired level of dynamic content, the static displacement fields are needed to capture attachment effects. Or rather, the static displacement fields enrich the dynamic mode superset since they represent local flexibilities. The latter static displacement fields will be further denoted as ‘static correction modes’ (SCMs). In case of many joints, bolted connections, contact, or in the case of distributed external loads, a combination of a limited number of global vibration modes and a huge number of SCMs increasingly often occurs. Different methods on the reduction of SCMs have been published in the past, see e.g. [5,33,37]. However, in the presence of a large number of SCMs, the computational efficiency of the multibody simulation is partly lost due to the huge number of equations which needs to be time integrated.

In the present contribution a method for a more efficient handling of multibody systems including elastic components is presented. It is assumed that the deformations of the latter elastic components are represented by a linear combination of global vibration modes and a huge number of SCMs. The present paper is organized as follows. In Sect. 2 the literature concerning the Buckens-frame and its implication will be briefly reviewed. The use of modes which have no rigid body content and therefore fulfill the conditions of the Buckens-frame, leads to remarkable simplifications in the equations of motion. As mentioned in the literature, each arbitrary set of modes can be transformed into such modes [13,27,30,38]. Therefore, we restrict ourselves to such mode bases. At the end of this section we will formally introduce the separation between ‘low-frequency’ and ‘high-frequency’ modes (LFM and HFM). In Sect. 3 the equations of motion will be formulated in terms of the latter-mentioned LFM and HFM. This is quiet straightforward but has been included into the paper for the sake of clarity and readability. The next section is devoted to the unfavorable nonlinear coupling between rotational rigid body motion and the superimposed relative deformation of the elastic structure. Note that some contributions in the literature suggest neglecting this coupling at all [4]. In the present paper this assumption has not been made. As a key message of this contribution, it will be shown that the coupling effects between the body’s rotational motion and deformations resulting from HFM are much smaller than the one between rotational motion and deformations resulting from LFM. Therefore, the coupling between rotational rigid body motion and deformations resulting from HFM can be neglected. Besides a mechanical interpretation, a defined limit is given which enables an automatic detection of LFM and HFM. In the following the conclusions of the latter sections are incorporated into the mass matrix of the equations of motion as well as in the quadratic velocity vector. This leads to an equation of motion where the HFM DOF are fully decoupled in the mass and stiffness matrix. On the basis of a priori known frequency range of interest the inertia effects of high-frequency terms resulting from HFM can be safely neglected in the equations of motion. In a next step, the equations of motion are modified so that those equations which are attributable to HFM DOF do not need to be time integrated at all. When the number of HFM is much higher than the number of LFM, the static condensation of HFM leads to a significant improvement in terms of computational effort without changing the quality of results. In the final section a numerical example with a large number of DOF (over 1 million) is presented in order to illustrate the applicability and to explore the accuracy of the proposed method. For the mode-based computation the likewise commercially available software package MSC. ADAMS has been used. The presented approach leads to excellent accuracy, and a significant save of computational effort can be reported.