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On the numerical modeling of sliding beams: A comparison of different approaches

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ABSTRACT

The transient analysis of sliding beams represents a challenging problem of structural mechanics. Typically, the sliding motion superimposed by large flexible deformation requires numerical methods as, e.g., finite elements, to obtain approximate solutions. By means of the classical sliding spaghetti problem, the present paper provides a guideline to the numerical modeling with conventional finite element codes. For this purpose, two approaches, one using solid elements and one using beam elements, respectively, are employed in the analysis, and the characteristics of each approach are addressed. The contact formulation realizing the interaction of the beam with its support demands particular attention in the context of sliding structures. Additionally, the paper employs the sliding-beam formulation as a third approach, which avoids the numerical difficulties caused by the large sliding motion through a suitable coordinate transformation. The present paper briefly outlines the theoretical fundamentals of the respective approaches for the modeling of sliding structures and gives a detailed comparison by means of the sliding spaghetti serving as a representative example. The specific advantages and limitations of the different approaches with regard to accuracy and computational efficiency are discussed in detail. Through the comparison, the sliding-beam formulation, which proves as an effective approach for the modeling, can be validated for the general problem of a sliding structure subjected to large deformation.

1. Introduction

The dynamics of sliding structures has been an important topic in structural mechanics due to its relevance in numerous engineering applications. By the term sliding structures, one typically refers to problems of beam or plate-like bodies that undergo a large translational motion with a superimposed flexible deformation. Early investigations on sliding structures were dealing with the deployment of flexible antennas [1], vibrations of band saws [2] and belt drives [3]. The nature of structures being transported in a preferred direction is intrinsic to many industrial processes as rolling in metal forming and paper production, for instance.

The present paper compares different approaches for the numerical modeling of dynamic problems of sliding structures. In particular, the focus lies on beam-like structures subjected to a planar, possibly large deformation. The classical sliding spaghetti problem serves as a benchmark example for the subsequent investigations. Inspired by the unfortunate event of

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spaghetti sauce being scattered from a noodle that is sucked into the mouth, the term sliding spaghetti is used for problems of beam-like structures that are retrieved into some kind of orifice. Another well-known example from everyday life similar to the spaghetti problem is that of a winding retraction of a tape measure. Both processes, i.e., sucking in a spaghetti and winding up a tape measure, share a common feature that is typical of this kind of problems. During the retraction of the structure, transverse vibrations of the part that yet remains to be retracted are gradually excited. Typically, both the frequency and the amplitude of the vibrations compared to the remaining length of the structure substantially increase towards the end of the retraction process.

From the modeling perspective, the sliding spaghetti problem involves several inherent difficulties that need to be addressed in the analysis. Obviously, problems of sliding structures involve large displacements due to the underlying translational motion, which is possibly accompanied by large flexible deformation. Large deformation problems in structural dynamics typically do not admit solutions in closed-form. For this reason, some numerical method is required to determine approximate solutions. Typical approaches, e.g., finite elements, employ a spatial discretization of the body under consideration, which relates to a second crucial feature of sliding structures, i.e., the relative motion with respect to their supports, which are usually fixed in space. As a consequence, support reactions imposed by kinematic constraints are not prescribed at fixed material points, but their points of action relative to the structure vary due to the sliding motion. Owing to these typical properties of sliding structures, a straight-forward modeling adopting a conventional finite element formulation of solid mechanics involves several pitfalls that need to be carefully addressed.

To alleviate numerical analysis, formulations specifically addressing the characteristics of sliding structures have been developed. Within the last decades, many different strategies have been presented to facilitate both analytical and numerical analyses of sliding structures. A complete review of the numerous contributions to the field of sliding structure is beyond the scope of the present paper. The common idea followed in many approaches is to represent the quantities involved not as a function of the material coordinate of the considered structure, but to use another suitably transformed coordinate as independent spatial variable instead. In the early contribution on vibrations of spacecraft antennas being deployed or retracted, Tabarrok et al. [1] used the Euler-Bernoulli beam theory for large deformation adopting Eulerian (spatial) coordinates. Their numerical analysis of the linearized problem by means of Ritz' method employs shape functions that depend on the instantaneous length of the considered structure. A similar approach was pursued by Buffinton and Kane [4] who analyzed a moving Euler-Bernoulli beam on two supports using linear beam theory. In the analysis, they used free-free modes of a beam with constant length which are constant in time with kinematic constraints being imposed to satisfy the supporting boundary conditions. Theodore and Ghosal [5] studied a flexible link manipulator sliding through a prismatic joint, with the manipulator being modeled as an Euler-Bernoulli beam. Stylianou and Tabarrok [6,7] presented a linear formulation for the flexural vibrations of an Euler-Bernoulli beam being retracted into a prismatic joint following a prescribed axial motion. They solved the equations using the finite element method, with a constant number of finite elements used on the part of the structure outside of the joint. Vu-Quoc and Li [8] presented a fully non-linear dynamic formulation for sliding beams based on the geometrically-exact theory [9,10] for shear-deformable beams. In their comprehensive study, which inspires much of the present work, they proposed two equivalent derivations for the equations of motion based on a stretched material (Lagrangian) coordinate and spatial (Eulerian) coordinates, respectively. The coordinate transformation present in the paper enables the use of conventional beam elements in the numerical analysis. An alternative derivation of the equations of motion of sliding beams by Behdinan et al. [11] is based on McIver's [12] extension of Hamilton's principle for systems with a variable mass. To obtain approximate solutions of dynamics, they employed a Galerkin's method [13] and compared two kinds of finite element formulations [14], i.e, beam elements with a variable and a fixed length, respectively. Gürgöze and Yüksel [15] investigated the vibrations of a beam sliding through a prismatic joint using the extended Hamiltons principle and solving the equations with a modal approach. Again, the axial sliding motion of the beam was prescribed kinematically in their investigations. Static problems of structures that can move relative to their supports were studied, e.g., in [16,17].

The contributions mentioned above share the fact that only a selected part of the structure under consideration is regarded in the analysis. In the case of the spaghetti problem, for instance, only the part outside the guide opening (mouth) would be described whereas the portion already sucked in is not accounted for. To describe the entire sliding spaghetti and the mutual influence of its inside part and outside part, Humer [18] presented a generalization of the formulation of Vu-Quoc and Li [8]. While restricting to slender beams that are rigid in shear, the extension allows for a larger range of boundary conditions as compared to earlier contributions.

Besides a generalization of [18] to shear-deformable beams, the proper representation of the kinematic constraints imposed on sliding structures is also one of the key aspects of the present paper. Indeed, the main aim of the subsequent investigations is twofold: On the one hand, the paper describes the crucial aspects involved in the numerical analysis of sliding structures by means of conventional finite element approaches that are available in commercial software such as ABAQUS [19]. The transient behavior of a sliding spaghetti, i.e., a beam being retracted into a guide, is investigated using both the (planar) relations of elasticity and Reissner's beam theory with the corresponding finite elements in ABAQUS. In either approaches, the interaction of the beam with its supports is represented by means of a conventional contact formulation. The paper shows that convergence and accuracy of the solution can be improved by adjusting the position and the shape of the opening of the guide in the numerical model. On the other hand, the sliding spaghetti problem is also analyzed using the sliding–beam formulation proposed by Humer [18]. Compared to [18], the sliding–beam formulation is extended to account for shear deformation, which turns out to be significant to accurately represent the beam behavior at the opening of the guide and when the beam becomes