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Research paper

An arbitrary Lagrangian–Eulerian discretization method for modeling and simulation of reeving systems in multibody dynamics

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ABSTRACT

This paper presents an efficient discretization method for the modeling and simulation of reeving systems using multibody dynamics. Reeving systems are assumed to include rigid bodies connected by a set of sheaves or reels and wire ropes. The method is based on line-parametrized Absolute Nodal Coordinate Formulation (ANCF) defined in the framework of an Arbitrary Lagrangian–Eulerian (ALE) description. In the ALE description the element nodes have variable material coordinates thus allowing the element to change its position within the flexible body. This property is very convenient to model wire ropes rolled in sheaves or reels that have variable-length free spans, as usually occurs in reeving systems. Axial-torsion elastic coupling of the wire ropes is also a very important effect to be considered in reeving systems. A set of locally defined cross-section rotation angles is introduced to describe this effect thus abandoning the ANCF formalism. This paper presents different options for the wire rope modeling depending on the problem dimension (1, 2 or 3D) and the assumed elastic force model. Depending on the application the method offers elements that can show axial, torsion and bending deformation energies or any combination of them. This paper presents a general procedure to model reeving systems and the numerical calculation of the resulting equations of motion. Two examples are presented: the dynamic model of a 2:1-suspended electrically-driven elevator and a quasi-static model of a large crane.

1. Introduction

Wire ropes, belts and cables are the most widely used machine elements that exhibit large deformation. The complex dynamic behavior of these solids and its fundamental influence in the overall behavior of the machine in which they operate deserve a special attention in multibody machine modeling. However general purpose or theoretical works in the field of large-deformable multibody systems [1–4] in many cases do not focus on the particular details of the modeling of wire ropes, belts or cables. These details include frictional contact with sheaves, localized deformation in the contact segment, transverse vibration in spans and axial-torsion elastic coupling in wire ropes. Finite element models face the fundamental problem of the elements length requirement which is small in the segments in contact with the sheave but relatively large in the spans. In the Lagrangian Finite Element approach short elements are needed for the whole rope discretization since

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any element can eventually be in contact with a sheave. Under these conditions finite element rope models become unefficient, being unsuitable for example for real-time applications. This paper shows how the combination of the Absolute Nodal Coordinate Formulation and the Arbitrary Lagrangian–Eulerian method (ALE-ANCF) [5] can alleviate this problem. Although the presented method can also be adequate to model the rope-sheave contact, this problem is not addressed in this paper.

Variable length wire rope was modeled using chain links modeled with lumped masses for marine applications in [6]. An alternative method to account for elasticity of the wire ropes considers them as linear springs with length-dependent stiffness and neglects inertia and weight forces [7]. This model can be sufficiently accurate in many applications. However, this method cannot describe lateral vibrations and it can be energetically inconsistent [8]. In order to consider the rope inertia and weight a lumped-parameters discretization (spring-mass model), the Raileigh–Ritz method [8] or non-linear finite elements can be used. The ANCF has been previously used to model cables [9–11] and belt-drive systems [12] facing the discretization problem explained in the previous paragraph. A recent publication by Hong and Ren [5] re-defines the ANCF using an Arbitrary Lagrangian–Eulerian (ALE) description. In that paper the method is applied to the modeling of sliding joints. This paper exploits the applicability of the ALE-ANCF method to the modeling of reeving mechanisms.

The elastic behaviour of wire ropes is treated in refs. [13,14]. While the book by Costello [13] shows an elegant theory of the wire ropes behaviour, the resulting theoretical results have difficulties to agree with experimental tests especially with the so-called *rotation resistant ropes* that are widely used in reeving systems. This book explains in detail the linear axial-torsion coupling that occurs in wire ropes. The book by Feyrer [14] is more experimentally oriented and presents a more appropriate quadratic axial-torsion elastic coupling for rotation resistant ropes. In this book a description of the tests and testing machines required to get the constants associated with the elastic behavior of the wire ropes are described.

The present work focuses on modeling the overall dynamic behaviour of machines with reeving systems. To this end wire ropes are modelled as rods. Classical rod models can be classified [15] into Cosserat, extensible Kirchhoff and inextensible Kirchhoff models, depending on whether shearing and extension, only extension or neither shearing nor extension are considered, respectively. These three classical rod models can describe bending and torsion of the rods. Shear deformation of wire ropes is very difficult to model because the cross section is actually a set of independent sections of the wires. In addition shear deformation of wire ropes is not important for the overall dynamics of reeving mechanisms. However torsion deformation of the wire ropes may have important influence in the dynamics and quasi-static behaviour of the reeving system. Due to these reasons the discretization procedure developed in this work is based on the extensible Kirchhoff rod model [16,17].

This paper presents a numerical method for the modeling and simulation of reeving systems as multibody systems. The model is based on the discretization of the wire ropes using an ALE mesh. Section 2 explains the suitability of the ALE description for the modeling of reeving systems. Section 3 presents the ALE-ANCF method that is basically the one introduced in [5] adding an alternative and simpler linear versions of the same element. Section 4 presents an original ALE element that introduces locally defined torsion angles for the description of axial-torsion elastic coupling in wire ropes. This new element can no longer be considered as an ANCF element. Section 5 shows the general procedure to model reeving systems with the elements presented in the previous sections. Section 6 provides simulation results using as examples a 1:2-suspension elevator and a large crane. The elevator example is a simple 1-D system that shows the application of the method to the analysis of the longitudinal dynamics of this machine. The crane example is an industrial application with relatively complex geometry that shows the application of the method to study the axial-torsion elastic coupling in reeving systems. This last problem is solved quasi-statically.

2. Ale approach for modeling reeving systems

In the Lagrangian-based finite element method (FEM) nodes are attached to material while in the Eulerian-based FEM nodes are fixed in space. The Lagrangian approach is common in solid mechanics while the Eulerian approach is more common in fluid mechanics. For the modeling of problems which are somehow in between, like large deformation problems that take place during metal-manufacturing, the Arbitrary Lagrangian–Eulerian approach was introduced [18]. In the ALE approach the finite element mesh is neither fixed to the material nor fixed in space. Instead the nodes are conveniently located to model the problem to be solved. This idea is very convenient for the modeling of reeving systems as it will be shown next.

The advantage of the ALE approach for modeling reeving systems is clearly observed in Fig. 1. The figure shows a 1:1-suspension elevator, that includes the drive sheave, the cabin and the counterweight, in two different positions. The drawing on the left shows the regular Lagrangian FEM discretization. The finite elements have equal length which is determined by the length needed to adequately model the rope-sheave contact (approximately one third of the sheave diameter in the drawing). Finally the model has many elements whose length is probably smaller than that needed to model the rope spans. A small length of the elements is needed because any of them may eventually come into contact with the sheave. The drawing on the right shows the ALE discretization. The elements length is uneven. Short elements are used in the segment in contact with the sheave while long elements (single elements in the figure) are used in the spans. This type of discretization is possible due to the ALE description. Finally much less elements are needed to model the system when using the ALE approach.

Contact modeling can also be improved with the ALE approach. In the Lagrangian mesh the elements that are coming into contact with the sheave have difficulties to describe the deformed shape. When contact starts the part of the element that