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Modelling of nonsmooth frictional yarn-to-mandrel contact interactions for braiding simulation

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1. Introduction

Braiding is the fundamental process in fabrication of preforms for composite production. On the one end, textile yarns flow from bobbin carriers in a controlled manner, driven by horn gears to form an interlocked mesh. On the other end, yarns undergo contact-friction interactions with the mandrel. The global process interactions are best captured by system-level models. Thus, we propose a multibody framework using Odin [1], where the carriers and the mandrel are modelled as rigid bodies, while the textile yarns are modelled as flexible beams. Phenomena such as tension compensation are modelled using judicious choices of kinematic joints, and carrier motions using switching bilateral constraints. In this work, we focus on the frictional yarn-to-mandrel contact interactions. For this investigation, the winding of a single yarn around the mandrel serves as a representative problem. Using nonsmooth models, the unilateral constraint can be expressed as a Signorini condition together with a Coulomb friction law.

2. Method

To solve the yarn-to-mandrel contact problem, two different approaches are considered in this work. Firstly, the mortar contact element proposed in [2] can be used provided that the yarns and the mandrel are both modelled as beams with circular cross-sections, and friction is neglected. The discrete quasi-static equilibrium is

$$\mathbf{f}^{\text{int}}(q(t)) + \mathbf{G}^T(q(t),t)\boldsymbol{\lambda}(t) = \mathbf{f}^{\text{ext}}(q(t)) \tag{1}$$

$$\mathbf{g}^{\overline{\mathcal{U}}}(q(t),t) = \mathbf{0}_{m\times 1} \tag{2}$$

$$\mathbf{0} \leq \boldsymbol{\lambda}^{\mathcal{U}}(q(t)) \perp \mathbf{g}^{\mathcal{U}}(q(t)) \geq \mathbf{0} \tag{3}$$

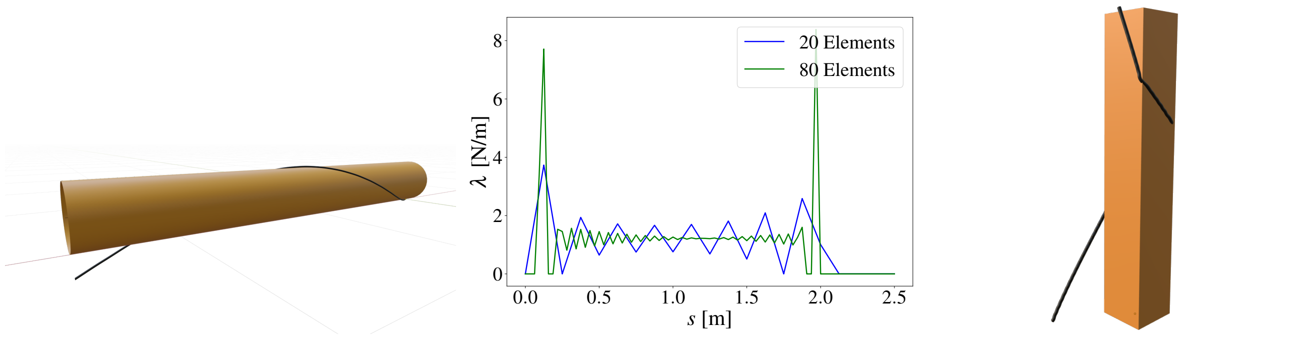
where q is the configuration on a Lie group, $\mathcal{U}$ denote the unilateral constraints, $\mathbf{g}^{\mathcal{U}}(q(t))$ is the contact gap, $\boldsymbol{\lambda}^{\mathcal{U}}$ is the normal contact forces, and $\overline{\mathcal{U}}$ are bilateral constraints. The Lagrange multipliers are defined as $\boldsymbol{\lambda} = \begin{bmatrix}\boldsymbol{\lambda}^{\mathcal{U},T} & \boldsymbol{\lambda}^{\overline{\mathcal{U}},T}\end{bmatrix}^T$. In the second approach, the mandrel is modelled as a rigid body, and proxy collision geometries represent the centerline of the yarn. Then, the Bullet library is exploited for collision detection. The time discrete equations are obtained using the nonsmooth generalized-α (NSGA) [3]. For instance at velocity level, the frictional contact problem in the tangential direction is expressed as

$$-(\mathbf{G}_T^j(q_{n+1})\mathbf{v}(q_{n+1}) + e_T^j\mathbf{G}_T^j(q_n)\mathbf{v}(q_n)) \in \partial\psi_{C(\Lambda_N^j(q_{n+1}))} \qquad \text{if } g_N^j(q_{n+1}) \leq 0, \tag{4}$$

where $\mathbf{v}$ is the velocity, $\mathbf{g}^j$ is the relative position for the contact j with the normal component g_N^j and tangential component $\mathbf{g}_T^j$, and e_T^j is the tangential restitution coefficient which is chosen as $e_T^j = 0$ for contact involving flexible bodies. Λ_N^j and $\boldsymbol{\Lambda}_T^j$ are the normal and tangential components of the Lagrange multiplier respectively representing the impulse, $\mathbf{G}_T^j$ is the tangential constraint gradient and $\psi_{C(\Lambda_N^j)}$ is the indicator function of the section of the Coulomb friction cone.

3. Simulation results for winding test

First, using the mortar method, we simulate the winding of a yarn around a cylindrical mandrel as shown in Figure 1a. The properties of the yarn are radius $r_y = 0.001$ m, length $l_y = 2.5$ m, $E = 110$ GPa, $\mu = 0.23$. The



(a) (b) (c)

Figure 1: (a), (b) Winding test on cylindrical mandrel using frictionless mortar approach: mesh size variation for Lagrange multiplier λ. (c) Winding test on rectangular mandrel using the frictional collocation approach.

properties of the mandrel are radius $r_m = 0.03$ m, length $l_m = l_y = 2.5$ m, $E = 210$ GPa, $\nu = 0.21$. Both the yarn and the mandrel are discretized using 20 beam finite elements. The simulation consists of 650 load steps, with a load increment applied every 0.01 fraction of the total process. Figure 1b shows the resulting evolution of the normal contact Lagrange multiplier λ as a function of the arc length parameter s. Numerical oscillations are expected from a finite element discretization [2]. The mortar method can handle nonsmooth distributed contact forces, but at the cost of oscillations. We compare the results obtained by using mesh sizes of 20 and 80 elements. The amplitude of the oscillations in the Lagrange multipliers decreases significantly for the mesh size of 80 elements. For the moment, the mortar formulation is not combined with a collision detection procedure, which limits the applicability to larger problems. Also, our current implementation is limited to beams with cylindrical cross-section and frictionless contacts.

Second, using the collocation approach and proxy collision elements, one can further extend this analysis by considering general mandrel shapes (having convex and concave contours) and friction. For instance, Figure 1c shows a textile yarn winding around a rectangular mandrel.

4. Conclusion

The mortar method is a viable choice to solve the yarn-to-mandrel contact problem, but it requires some extension for the simulation of general cases. The collocation method with proxy collision elements can efficiently deal with frictional contact, arbitrary mandrel shapes, and can accomodate a high number of yarns.

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