# Formulation and Analysis of Sliding Joints with Clearances in Flexible Multibody Systems

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Sliding joints between flexible beams and rigid holes have been widely used in flexible multibody systems. When the flexible beams are initially curved or the sliding joints are under zero gravity, the clearance of sliding joint may have significant influence on the dynamic performance of flexible multibody systems. The objective of this paper is to develop the model of the sliding joint with clearance and analyze the influence of the clearance of sliding joint. The flexible beam is formulated using the three-dimensional curved Euler-Bernoulli beam element of the Absolute Nodal Coordinate Formulation[1][2], while the motion of the rigid hole is described by the Cartesian coordinates[3].

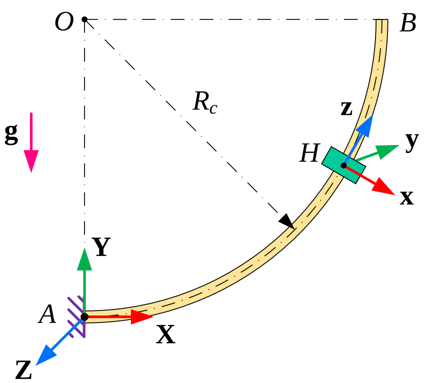
The existing joints with clearances are mainly rigid joints with small clearances, and the contact detection algorithm adopted can solve only one pair of potential contact points within one section. In order to model the contact problem in the sliding joint with clearance, a new contact detection method is proposed.

The method proposed here is based on the following assumptions: (1) The cross-sections of flexible beams and rigid holes are supposed to be circular. (2) The contact detection problem can be simplified to find the potential contact points on the flexible beam and a finite number of cross-sections of the rigid hole. (3) The bending deformation of the flexible beam near the contact point is small. (4) In the case of initially curved beams, the clearance of sliding joint is much smaller than the radius of curvature.

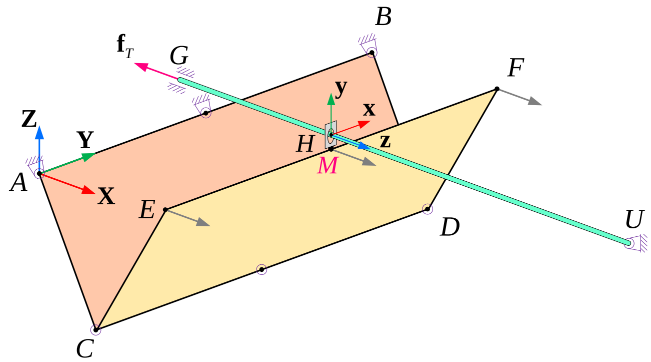
The detailed contact detection procedures are presented as follows: (1) First, the elliptical intersection of the rigid hole's cross-section and the flexible beam is determined, including the global position vector $\mathbf{r}_I$ of the center of this ellipse, two unit vectors $\mathbf{e}_a$ and $\mathbf{e}_b$ representing the semi-major axis and the semi-minor axis, respectively, as well as the lengths $a$ and $b$ of the semi-axes. (2) Then, the original three-dimensional contact detection problem can be reduced to a two-dimensional one, *i.e.* the ellipse-circle contact detection within the rigid hole's cross-section. Based on the common-normal concept[4], the necessary conditions for contact are summarized, and the angle representing the contact direction can be solved by using the Newton-Raphson iteration method. In addition, the multiple-point contact will occur when the maximum radius of curvature of the ellipse $\rho_{\max} = a^2/b > R$, where $R$ is the radius of the circular cross-section of the rigid hole. (3) The potential contact point $Q$ on the hole's cross-section will be determined, and the closest point projection $P$ of the point $Q$ on the beam's neutral axis can be defined by solving a minimization problem[5]. (4) When the distance between the two points $P$ and $Q$ is less than the radius of the circular cross-section of the beam, the contact between the flexible beam and the rigid hole occurs, and the penalty method is adopted to enforce the normal non-penetration condition. The proposed contact detection method can deal with the sliding joint with large clearance and the multiple-point contact problem within one section.

Two numerical examples are presented to demonstrate the influence of the clearance of sliding joint on the dynamic performance of flexible multibody systems, and the cylindrical sliding joint[6] is adopted to evaluate the case when the clearance is not taken into account. The first example concerns the sliding joint with clearance between an initially curved beam and a hollow cylinder under gravity (see Fig. 1(a)), while the second one depicts the sliding joint with clearance between a guide wire and a grommet in a simplified model of the solar array wing[7] under zero gravity (see Fig. 1(b)). The large clearance between the guide wire and the grommet, as well as the multiple-point contact problem within the middle cross-section of the grommet are successfully solved by the proposed contact detection method (see Fig. 2(a) and Fig. 2(b)). Obvious distinctions in the dynamic responses of the guide wire and the panels arise when the clearance is considered (see Fig. 2(c) and Fig. 2(d)).

The contact detection method proposed here could be extended to more general $C^1$-continuous sections, like the approximate rectangular cross-section described by the superellipse curve.

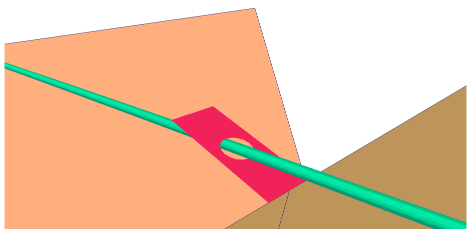



(a) A hollow cylinder slides along an initially curved beam under gravity

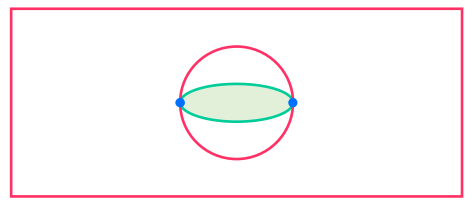



(b) A simplified model of the solar array wing under zero gravity

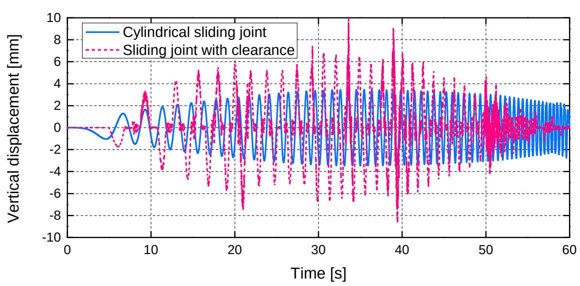
Fig. 1: Numerical examples



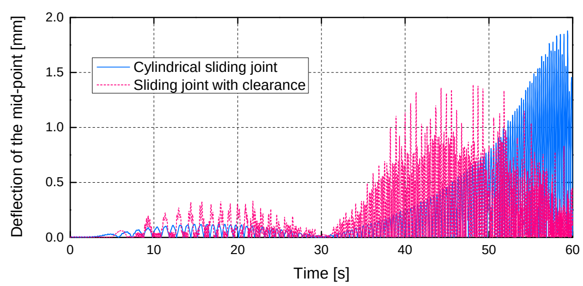
(a) Local details of the configuration at $t$ = 20 s



(b) Elliptical intersection within the middle cross-section of the grommet at $t$ = 20 s




(c) Vertical displacement of the mid-point of the guide wire




(d) Deflection of the mid-point of the edge $CE$

Fig. 2: Dynamic responses of the simplified model of the solar array wing

# References

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