Interface Models for the Simulation of Mechanical Clearances

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EXTENDED ABSTRACT

1 Introduction

The forward-dynamics simulation of mechanical systems subjected to joint clearances is often a computationally expensive task. The simulation of unlubricated clearance requires the characterization and modelling of rigid-body impacts, which have traditionally been performed by means of constitutive relations and penalty methods [1], leading to stiff systems that require small integration step sizes. Alternative nonsmooth dynamics approaches, that result in complementarity problems, have been proposed as well [2]. Regardless of the selected solution, such simulations are computationally intensive, even in the study of relatively simple mechanical systems.

In some cases, the accuracy requirements imposed on the simulation results can be relaxed to speed up code execution. This is the case, for instance, when simulation is used to provide numerically generated data to train neural networks, or to provide a model for state estimation. In this context, rather than a high-fidelity prediction of the time-history of the system dynamics, the expected output of forward-dynamics simulation is a set of data that captures the fundamental behaviour of the system under study. The interface model here presented serves this purpose. It is based on the assumption that the time-history of the system configuration and velocity can be approximated by that of an ideal representation without joint clearances, which is often the case in the initial stages of defect evolution. The dynamics of this ideal system can be simulated with efficient multibody algorithms, avoiding the need to use small integration step sizes, as

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{f} + \mathbf{A}^{\mathrm{T}}\boldsymbol{\lambda}, \qquad \text{subjected to} \qquad \boldsymbol{\Phi} = \mathbf{0} \tag{1}$$

where $\mathbf{q}$ stands for the generalized coordinates of the system, $\mathbf{M}$ is the mass matrix, $\mathbf{f}$ includes the forces acting on the system, $\boldsymbol{\Phi}$ is the term of kinematic constraints, $\mathbf{A} = \partial\boldsymbol{\Phi}/\partial\mathbf{q}$, and $\boldsymbol{\lambda}$ is a set of Lagrange multipliers. The clearance itself can be represented separately, by means of the geometries of the bodies in contact at the joint where the defect is present. It is possible to express the overall system dynamics in terms of the relative velocities $\mathbf{w}$ of the bodies allowed by the clearance in this interaction subspace, as exemplified in Figure 1 with a slider-crank mechanism.

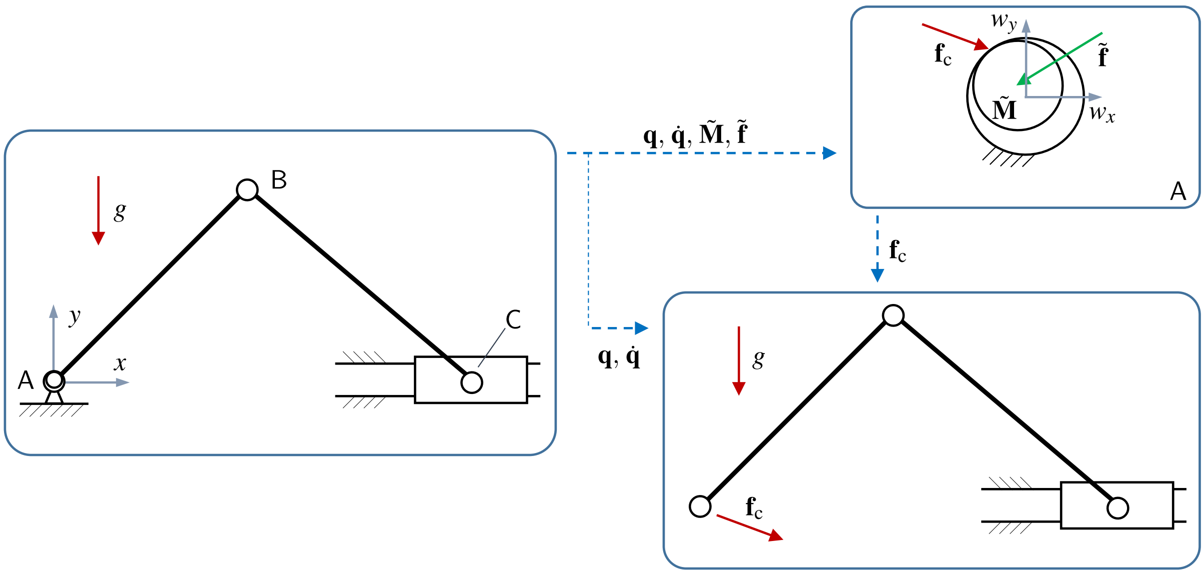

Figure 1: Interface model for a slider-crank mechanism with a clearance in the first joint.

The dynamics of the interface system can be expressed as

$$\tilde{\mathbf{M}}\dot{\mathbf{w}} = \tilde{\mathbf{f}} + \mathbf{f}_{\mathrm{c}} \tag{2}$$

where $\tilde{\mathbf{M}}$ and $\tilde{\mathbf{f}}$ are the effective mass matrix and force term of the interface. These terms were defined in [3] in the context of co-simulation environments for mechanical systems. They are evaluated directly from the configuration, velocity, and mechanical properties of the ideal system model, which can be integrated with a relatively large step-size, e.g., $h_{\mathrm{m}} = 10^{-3}$ s. Term $\mathbf{f}_{\mathrm{c}}$ stands for the forces transmitted at the interface, e.g., those caused by the contact between the bodies. Equation (2) is integrated with a step size small enough to adequately describe the contact and impact phenomena at the clearance, e.g., $h_{\mathrm{r}} = 10^{-5}$ s. Finally, the contact forces $\mathbf{f}_{\mathrm{c}}$ evaluated with the interface model are propagated to the complete mechanism to evaluate their effect on the generalized accelerations. This last step is necessary because sensors are often mounted on locations different from the joints affected by clearance.

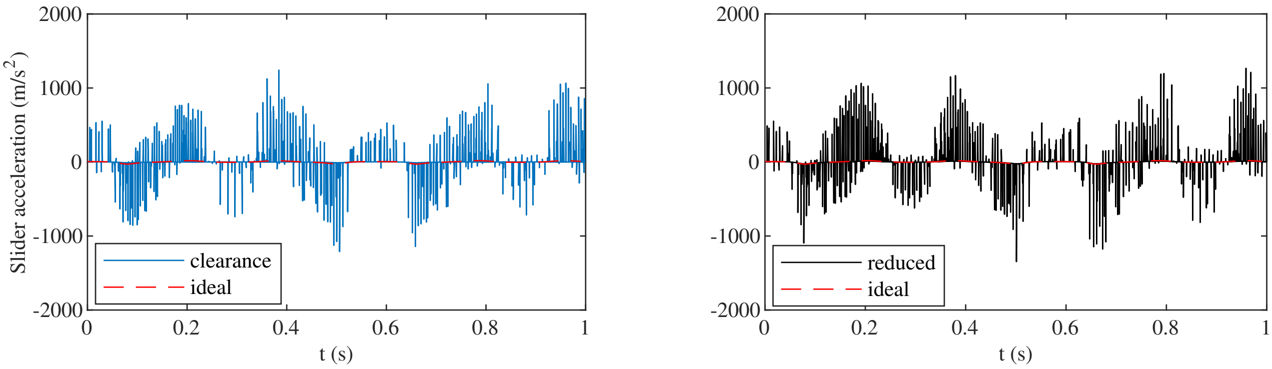

Figure 2: x-acceleration of the slider with a 100 μm clearance radius.

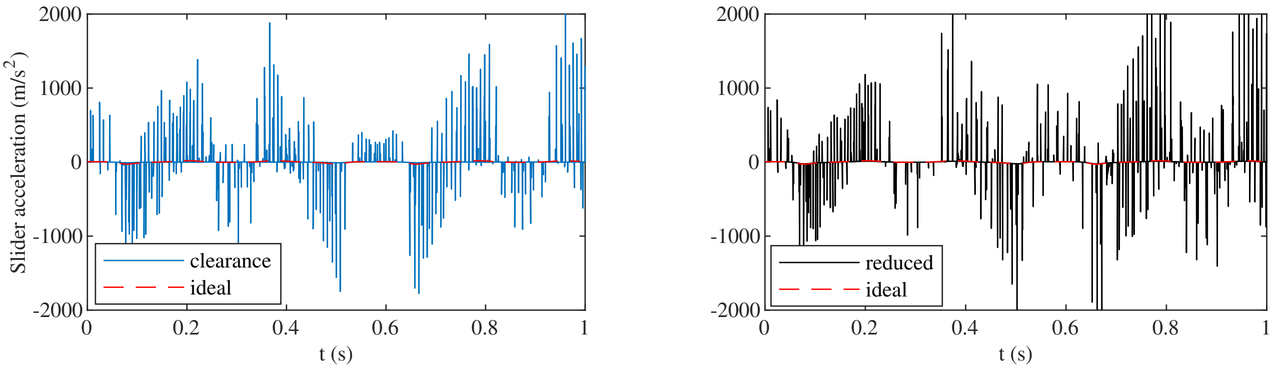

Figure 3: x-acceleration of the slider with a 200 μm clearance radius.

Figures 2 and 3 show the x acceleration of the slider evaluated with a multibody model of the linkage that includes a clearance at joint A. Results from the reduced model reproduce the behaviour predicted by the full-size multibody model, which requires an integration step-size $h = 10^{-5}$ s to correctly capture the contact phenomena at the clearance, enabling a reduction of the total time elapsed in computations of an order of magnitude for the presented example.

Acknowledgments

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