A non-invasive system-level model order reduction scheme for flexible multibody models

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This work present a novel non-intrusive approach for system-level model order reduction for (small-deformation) flexbile multibody simulation (FMBS). The general aim of system-level model reduction, in contrast to the classical component level reduction employed in FMBS, is to both obtain a relatively low order model and to transform the equations of motion into a set of ordinary differential equations. This in turn leads to a model description which is much more suitable for a range of applications, like state-estimation and model based control. However, previously proposed system-level model order reduction methods required access to model information which could not be (easily) extracted from commercial multibody software [1, 2, 3]. In this work we therefore propose an approach which builds the system-level reduced order model (ROM) from generally accessible information, being the component finite-element system matrices and the nodal coordinates from the original FMBS simulation. This provides a framework which allows to use any common multibody software to set up the data to perform the system-level reduction which then yields a new compact model. An overview of the data exchange for this approach is shown in Fig. 1.
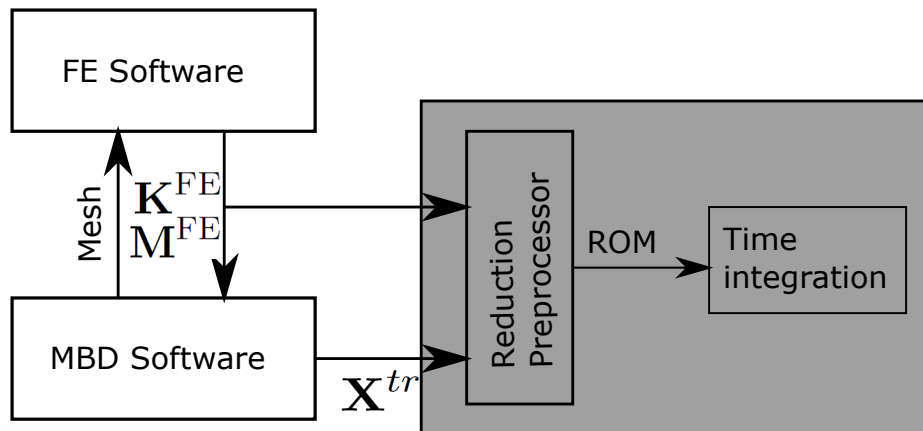

Fig. 1: Data exchange for system-level flexible multibody formulation.

In the proposed approach, a small-deformation flexible multibody model is first defined in a (commercial) multibody software. The original model is simulated for a (range of) relevant case(s). The nodal displacements are computed for these cases and combined in the training matrix $\mathbf{X}^{tr}$. This data is extracted from the multibody software and passed to the pre-processor for the reduced order model. Also the component finite element information (lumped mass and stiffness matrices) are passed to this pre-processor.

In the pre-processor, a system-level reference configuration $\boldsymbol{\rho}$ and reduced order basis $\boldsymbol{\Phi}^{\text{sl}}$ are computed. For the reference configuration $\boldsymbol{\rho}$, any of the simulated configurations can be selected. The reduced order basis $\boldsymbol{\Phi}^{\text{sl}}$ is obtained from a truncated singular value decomposition (truncated to the first m singular values) on the training data:

$$\boldsymbol{\Phi}^{\text{sl}} = \text{svd}(\mathbf{X}^{tr}, m). \tag{1}$$

This allows the nodal coordinates of the flexible bodies to be approximated as:

$$\mathbf{x} = \boldsymbol{\rho} + \boldsymbol{\Phi}^{\mathrm{sl}}\mathbf{q}, \tag{2}$$

where $\mathbf{q}$ are the reduced system level coordinates. As the reduced order basis is constructed from a set of coordinates which comply with the joint constraint equations of the flexible multibody model, it can be shown that this reduction space inherently complies with these constraints and they should not be accounted for anymore in the reduced order model. Moreover, in contrast to previous methods [1, 2], the proposed approach can employ a constant reduction space which greatly simplifies the reduced order model. In the next pre-processing step, the reduced order basis and finite-element model matrices are combined to set up a set of invariants required to evaluate the system level reduced order model. More particularly, this is a constant mass matrix $\mathbf{M}^{\mathrm{sl}}$ and a set of stiffness invariants. This particular structure is obtained by following a process similar to the internal energy formation for the Generalized Component Mode Synthesis [4]. In this approach the internal forces are evaluated for a set of global coordinates and a component rotation matrix is employed to evaluate the local deformation by rotating to the finite-element reference system.

The structure set up in the pre-processor leads to the equations of motion for the reduced order model:

$$\mathbf{M}^{\mathrm{sl}}\ddot{\mathbf{q}}^{\mathrm{sl}} + \mathbf{g}^{\mathrm{int}}(\mathbf{q}^{\mathrm{sl}}) = \left(\boldsymbol{\Phi}^{\mathrm{sl}}\right)^{T}\mathbf{f}^{\mathrm{ext}}, \tag{3}$$

where $\mathbf{g}^{\mathrm{int}}$ are the nonlinear internal elastic forces which are evaluated from a set of stiffness invariants defined on the system level degrees-of-freedom. This is now a simple set of ordinary differential equations on which a range of time-integrators can be applied. This equation structure also lends itself perfectly for further processing applications, like model based estimation and control.

The proposed model order reduction methodology is demonstrated on a number of flexible multibody models, demonstrating its general applicability and easy coupling to different existing software packages.

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