Co-Simulation Interface Reduction Based on the Flexible Natural Coordinates Formulation

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May 29, 2024

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Abstract

1 Introduction

Integrating two research domains using co-simulation presents an effective method for enhancing simulation complexity without mandating extensive familiarity with the external model. This approach only necessitates information on the input and output of the external model. In certain scenarios, such as Fluid-Flexible Structure coupled simulations, substantial sets of input and output data must be exchanged. For instance, these simulations demand the provision of the flexible structure's position to the fluid model and, reciprocally, the fluid model provides data on the distributed force affecting the structure. Consequently, substantial data structures are exchanged at specific time intervals, potentially becoming a critical aspect within the co-simulation framework.
To mitigate the data exchange burden in the co-simulation interface, we propose a reduction method based on the Flexible Natural Coordinates Formulation (FNCF), specifically tailored for small deformation flexible multibody simulations [1]. The objective of this interface reduction strategy is to limit the required interface points, leveraging the generalized coordinates affiliated with the FNCF framework.

2 Methodology

The interface reduction is based on the constant transformation matrix that connects the generalized FNCF coordinates to the Cartesian coordinates of a finite element mesh:

$$\mathbf{U}_{full} = \mathbf{r}_q \mathbf{q}, \tag{1}$$

with $\mathbf{U}_{full} \in \mathbb{R}^{3N}$ representing the full set of Cartesian nodal positions, $\mathbf{q} \in \mathbb{R}^{(12+10n)}$ the set of generalized FNCF coordinates and $\mathbf{r}_q \in \mathbb{R}^{3N\times(12+10n)}$ the constant transformation matrix. In general, $3N$ is much larger than $12+10n$ where N represents the number of nodes in the finite element model and n represents the number of mode shapes that are considered in the FNCF description.
The generalized coordinates set $\mathbf{q}$ can be estimated by a minimal set of interface nodes $\mathbf{U}_{int} \in \mathbb{R}^{(12+10n)}$ as:

$$\mathbf{q} = (\mathbf{r}_{int})^{-1}\,\mathbf{U}_{int}, \tag{2}$$

where $\mathbf{r}_{int} \in \mathbb{R}^{(12+10n)\times(12+10n)}$ and $\mathbf{U}_{int}$ are obtained through the effective independence methodology, applied to the transformation matrix $\mathbf{r}_q$ [2]. This results in an interface reduction equal to:

$$\mathbf{U}_{full} = \mathbf{r}_q\,(\mathbf{r}_{int})^{-1}\,\mathbf{U}_{int}. \tag{3}$$

However, if $\mathbf{r}_q$ contains linearly dependent mode shapes, $(\mathbf{r}_{int})^{-1}$ does not exist. Therefore, $\mathbf{r}_q$ requires to be orthogonalized before $\mathbf{r}_{int}$ is created. This orthogonalization can be performed through a Modified Gram-Schmidt methodology, as described in [3].

3 Numerical validation

For the numerical validation, we examine a beam connected to N springs, as illustrated in Figure 1. The beam undergoes loading with a cyclic force F having a magnitude of $1N$ and a frequency of $15Hz$, while each spring possesses a stiffness of $k = 10N/m$. We conduct three simulations for this setup.
The initial simulation involves a monolithic system where both the beam deflection and the spring forces

are calculated concurrently. This simulation serves as the reference point due to its expected higher accuracy. The subsequent model employs a co-simulation approach, establishing a complete interface between the springs and the beam nodes. Lastly, the third model adopts a reduced interface co-simulation, utilizing only a subset of interface nodes for data transfer.

To gauge the co-simulation's accuracy, a comparison is made between the full interface co-simulation model and the monolithic model, establishing a baseline for the co-simulation error. Additionally, a comparison between the full interface co-simulation and the reduced interface co-simulation is created to evaluate the interface reduction error. This analysis reveals that the interface reduction error is significantly smaller than the co-simulation error. Consequently, the outcome underlines the effectiveness of the reduced co-simulation interface, which downsizes the required interface points from 501 to 38. All corresponding plots are displayed in Figure 2.

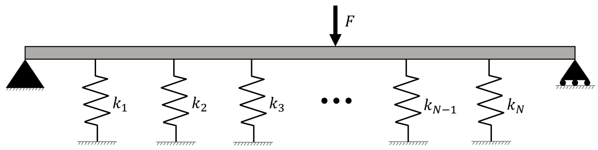

Figure 1: Loaded beam connected to springs.

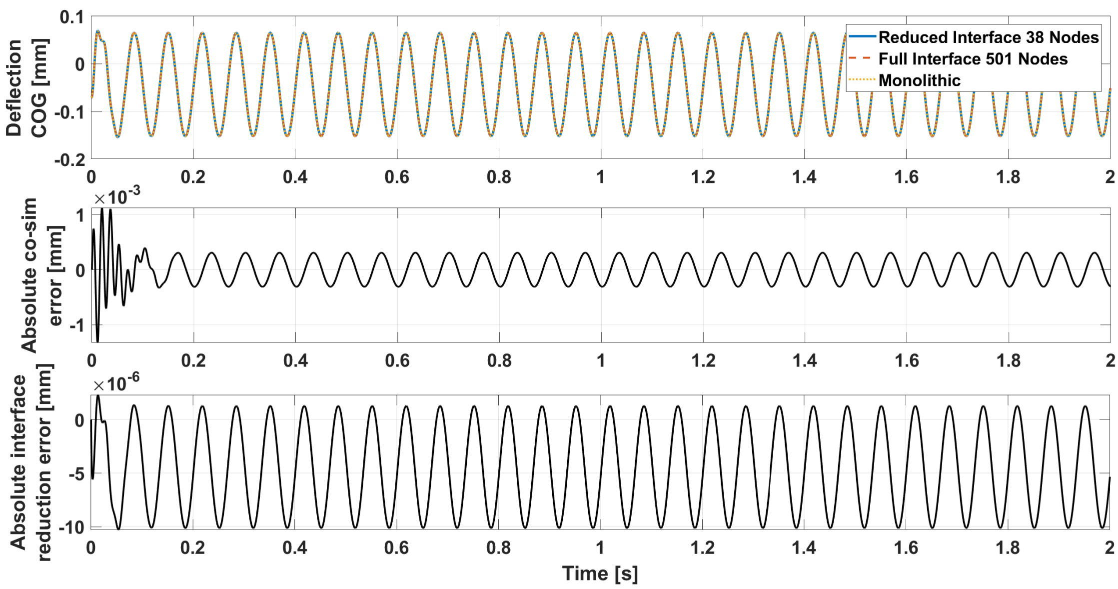

Figure 2: Comparison results of the monolithic model, full interface model and the reduced interface model.

Acknowledgments

The Internal Funds KU Leuven are gratefully acknowledged for their support. The Flanders Innovation & Entrepreneurship Agency, within the MODEMA project, is gratefully acknowledged for its support.

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