A Hybrid Methodology for the Determination of System Level Sensitivities Employing Multi-Body Co-Simulations of Mechatronic Systems

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Introduction

Over the years, it has been established in both research and in industry, that the design and modelling of mechatronic systems is a complex process. Therefore, many commercial software tools have been developed that enable accurate and rapid modelling of these systems. Using these system models, it is possible for the designers to simulate the behaviour of the system beforehand without the need for accurate prototypes, which reduces the cost to market. However, the increasing demand for optimized designs of complex mechatronic systems entails a need for novel modelling and optimisation tools to aid the designers in the design process. This work proposes an approach to enable design optimisation and parameter identification, through a novel method to compute system level sensitivities. Determining these system level sensitivities for mechatronic systems is no simple task, as mechatronic systems, by definition, consist of multiple different types of system models where it is common that a single design parameter influences different engineering domains included in the mechatronic system. In such a case, it is needed to obtain the local sensitivities from each of the engineering domains or submodels and combine them into a system level sensitivity that represent the influence of this design parameter on the full mechatronic system.

FMI based co-simulation

To determine these system level sensitivities of a mechatronic system, it is opted to co-simulate the different components or models of the mechatronic system. In this work, this is done using an in-house 'Multi-Body Research Code (MBRC)' [3] to simulate the dynamic components of the system connected to Functional Mock-up Units (FMU) [1] which act as external mathematical body's representing the remaining system models of the mechatronic system. An in-house tool has already been developed to obtain the system level sensitivity of the dynamic components employing the adjoint state method [2]. However, as the dynamic model has been extended with external components in the form of FMUs, it is required to expand the formulation of the adjoint state method with the local sensitivities coming from these FMUs. The main focus of this work lies in determining these local sensitivities from the FMUs. There are two types of local sensitivities that should be included in the formulation, being the one from the inputs of the FMU to its outputs and the one from the variation of the design parameter to the outputs of the FMU. The methodology proposed in this work is generally applicable to both types.

Local sensitivity analysis

The Functional Mock-up Interface (FMI) used to set up the FMUs is a generalized interface that has been developed for setting up co-simulations between different system models which have been modelled in different software packages. An additional benefit of the FMUs, is that when they have been compiled, they act as black box models so that it is no longer possible to extract any model information. This allows for FMUs to more easily be shared between company's. The methodology that is proposed in this work tries to maintain this benefit by determining the local sensitivities purely based on in- and output data or on additional simulation runs of the FMUs. In other words, no additional model information is needed.

Three different methods to determine the local sensitivities are proposed in this section. The presented methodology will be a hybrid solution combining these different methods. The first method is called the 'perturbation analysis' (PA). The main idea behind this method is shown in figure 1 on the left. At each time step of the simulation, a copy is made of the FMU and a slightly perturbed input (I) is applied to this copy.

By comparing the output (O) of the FMU to that of the perturbed FMU, a numerical value is determined for the local sensitivity. An important aspect of this method, is that at each time step an exact copy of the FMU is made to apply the perturbed input to. This requires saving and setting all the internal states of the FMU. As not all FMUs allow this functionality, it is necessary to look for alternative methods.

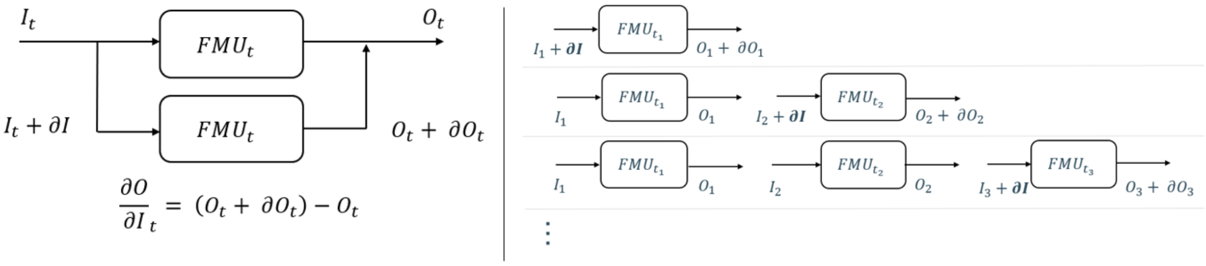

Figure 1: Schematic overview of the perturbation analysis (left) and the brute force method (right)

The second method is referred to as the 'brute force' (BF) method which is an adaptation of the PA method. Figure 1 on the right provides a schematic overview of this method. By solving the FMUs at each time step starting from their initial condition up to the current time step it is possible to overcome the need for knowing the internal states of the FMU as was the issue in the PA method. The perturbation is then again applied in the current time step and the local sensitivity is obtained in the same manner is in the PA method. This method is applicable to any FMU but, however, it is very slow as the FMU has to be solved $\frac{1}{2}n(n+1)$ times, where n is the amount of time steps.

This led to the final method which employs the 'finite difference' (FD) method to obtain the local sensitivity. In this method no additional callbacks are required to the FMU, instead the simulation in- and output data is used directly to determine a numerical estimate for the local sensitivity. This is done using the finite difference formulation,

$$aO(I_t) + bO(I_{t-1}) + cO(I_{t-2}) \approx \frac{\delta O}{\delta I} \tag{1}$$

where O represents the output signal, I the input signal and $a, b, c = f(I_t - I_{t-1}, I_{t-1} - I_{t-2})$ are the finite difference parameters. The main benefit of the FD method is that it does not require additional callbacks to the FMU which make it a fast method to compute the sensitivity. However, it has a limited applicability in that it can only be used to determine the sensitivity of models without any internal dynamics. Otherwise it is possible that the internal dynamics influence the output of the FMU making the result unreliable.

Each of these methods has their own limitations or has only a limited applicability, therefore a hybrid methodology is proposed. In this hybrid methodology a logical scheme is followed where the requirements of the methods are checked. In this way it is ensured that for each FMU, the best possible method is used to determine the local sensitivities. Further research will focus on expanding this logical scheme and possibly researching additional methods to determine the local sensitivities.

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References

[1] T. Blochwitz, et al., "The Functional Mockup Interface for Tool independent Exchange of Simulation Models Proceedings", 8th Modelica Conference, Dresden, Germany, March 20-22, 2011

[2] S. Vanpaemel; W. Desmet; F. Naets, Sensitivity Analysis of Flexible Multibody Systems. With Applications in Parameter, Topology and Input Optimization, 2022

[3] M. Vermaut; W. Desmet; F. Naets, "Flexible Natural Coordinates Formulation (FNCF): Towards Simpler Equations of Motion for Flexible Multibody Models", 2022, Ph.D. thesis, KU Leuven