MULTIBODY SIMULATIONS WITH REDUCED ORDER FLEXIBLE BODIES OBTAINED BY FEA

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Abstract

Tighter specifications in synchrotron instrumentation development force the design engineers more and more often to choose a mechatronics design approach. This includes actively controlled systems that need to be properly designed. The new Nano Active Stabilization System (NASS) for the ESRF beamline ID31 was designed with such an approach.

We chose a multi-body design modelling approach for the development of the NASS end-station. Significance of such models depend strongly on its input and consideration of the right stiffness of the system's components and subsystems. For that matter, we considered sub-components in the multi-body model as *reduced order flexible bodies* representing the component's modal behaviour with reduced mass and stiffness matrices obtained from finite element analysis (FEA) models. These matrices were created from FEA models via modal reduction techniques, more specifically the component mode synthesis (CMS). This makes this design approach a combined multibody-FEA technique.

We validated the technique with a test bench that confirmed the good modelling capabilities using reduced order flexible body models obtained from FEA for an amplified piezoelectric actuator (APA).

INTRODUCTION

To meet it's tight requirements in terms of precision and stability, a "model based design" approach was chosen for the development of the new ID31 end-station [1]. This type of design approach joins the need for dynamical models to test control architectures and to help specifying the requirements in the detail design stage.

We used a *MATLAB Simscape* multibody model for the detailed modular based design which is used to simulate the dynamical behaviour of the system. These models consist of *SIMULINK*-typical blocks, each representing one body or link. Such models were formerly limited to simple rigid bodies linked by "weak" links. They can be used as a first approximation. However, performances are often limited by resonances of flexible elements, i.e. the approximation by multiple solid bodies is not valid anymore.

Since recently, such *Simscape* models can be extended by a block named "Reduced Order Flexible Solid" (see Fig. 1a). This body consists of several interface points (here 5 points) and reduced FEA stiffness $\hat{\boldsymbol{K}}$ and mass matrices $\hat{\boldsymbol{M}}$ that describe its dynamical characteristics. This extends the body's represented behaviour in the simulations from pure inertial rigid-body representation to elastically deformable behaviour.

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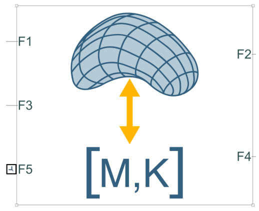
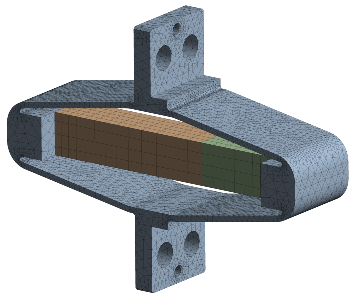


(a) Implementation of reduced order model in *Simscape* multibody simulation block [2].



(b) Meshed FEA model of an amplified piezoelectric actuator. Number of nodes: ≈ 130 000.

Figure 1: Flexible body used in a *Simscape* model as a reduced model from a fully meshed FEA model.

Application: Amplified Piezo Actuator

For the ID31 nano-end-station development we applied the FEA modal reduction technique to obtain reduced stiffness $\hat{\boldsymbol{K}}$ and mass matrices $\hat{\boldsymbol{M}}$ of key flexible components. This enables us to accurately model the dynamic behaviour of the end-station's nano-active-stabilization-syste (NASS) hexapod. We applied the method on the hexapod struts containing amplified piezo actuators (type APA300ML, [3]) and flexible joints. We model the APAs as reduced order flexible bodies, which is explained in this paper. Fig. 1b shows the fully meshed FEA model of the APA that we used for that matter. For the modal reduction of these APAs we used the commercial FEA software *ANSYS*. The resulting data was used as in input in the *Simscape* multibody analysis.

REDUCTION OF AMPLIFIED PIEZO

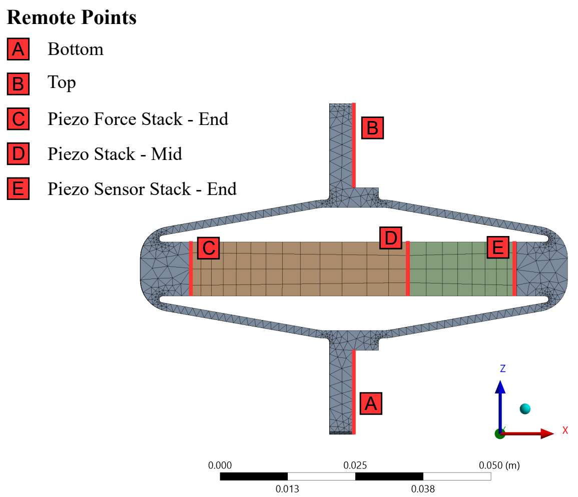
We applied the modal reduction technique from FEA (also called component mode synthesis) for the reduction of the high number of FEA degrees of freedom (DoF) to a smaller number of retained degrees of freedom[1]. For the example of the APA in Fig. 1b this results in a reduction from about $130\,000 \times 3 = 390k$ DoF of the 3D FEA model down to only tens of DoFs, as explained in the next section. This reduced amount of DoF makes the model easy to integrate in a multibody simulation.

FEA Modal reduction model

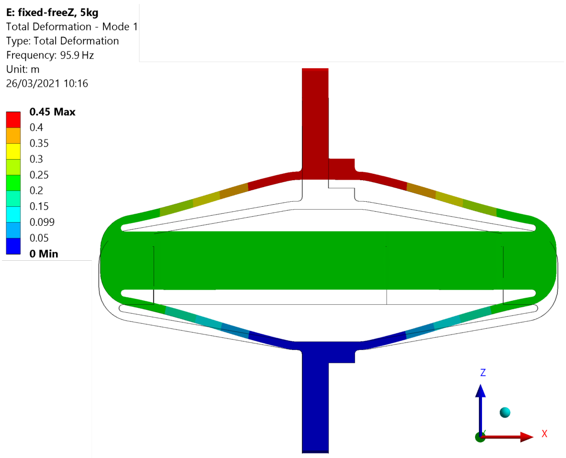
The *ANSYS* FEA model used for the modal reduction is shown with the used meshed in Fig. 2a. The points A to E mark the interfaces that were linked via a multi-point-

[1] Additional info on our applied procedure can be found in: `http://doi.org/10.5281/zenodo.5094419`

constraint to a pilot node (called remote points in *ANSYS*) on respective reference locations, as explained in the provided appendices. This couples the movement of the chosen interfaces to the pilot nodes.



(a) ANSYS modal reduction model with labeled retained interface "remote points" (A to E).



(b) Modal analysis total deformation results. The plot shows the first mode at $f_1 = 95.9$ Hz from FEA with 5 kg point mass attached to top node. Bottom node fixed and top node only free in z-direction.

Figure 2: Super element generation model and first mode from FEA.

The modal reduction was then performed retaining only the 6 DoFs of each of the 5 shown points, thus resulting in $m = 6 \times 5 = 30$ retained physical DoFs. In addition, $p = 6$ additional Eigenmodes were retained, creating 6 additional generalized coordinates. This procedure results in the reduced mass $\hat{\boldsymbol{M}}$ and stiffness matrices $\hat{\boldsymbol{K}}$ to be both square-matrices of length size $(m + p) \times (m + p) = 36 \times 36$. Thus the whole flexible behaviour of the reduced APA is now represented by these 36 DoFs. We used the "fixed-interface method", also called "Craig-Bampton-method" for the reduction [4, 5].

Table 1: Material properties used for the FEA modal reduction model in Fig. 2a. Stated data: Young's modulus E, Poisson ratio ν and density ρ.

	E GPa	ν –	ρ kg /m^3
Stainless Steel	190	0.31	7800
Piezoelectric Ceramics (PZT)	49.5		

Table 1 lists the material properties used for the reduction model. The stainless steel properties were fixed for the frame, whereas the Young's modulus E for the piezo-eletric material PZT was obtained by matching the vendors specifications[2] in terms of linear static stiffness ($k_s = 1.79\,\mathrm{N\,\mu m^{-1}}$) free-free Eigenfrequency and blocked-free Eigenfrequency as good as possible. The result is typical for PZT data.

We confirmed the model by verifying also the first Eigenfrequency for the blocked-free condition and an added load of $m = 5$ kg to the top. The result is shown in Fig. 2b. From the vendors specifications for stiffness and given load this should result in

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{k_s}{m}} = 95.3\,\mathrm{Hz}, \tag{1}$$

which is very close the calculated FEA result for the discrete model of $f_{1,FEA} = 95.9$ Hz.

Test-bench for model validation

A test bench shown in Fig. 3 was used to identify the dynamical behavior of the APA and to validate the reduced order model of the APA. To do so, a *Simscape* model of this bench was developed with the APA being modeled with the reduced order model. Both measured dynamics can then be compared.

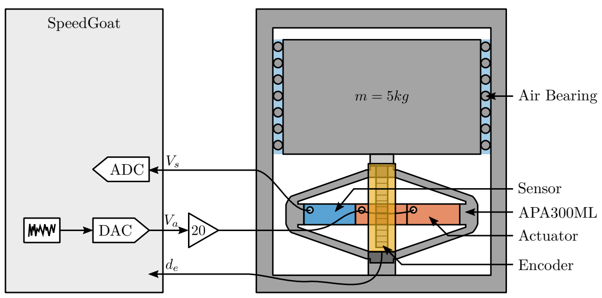
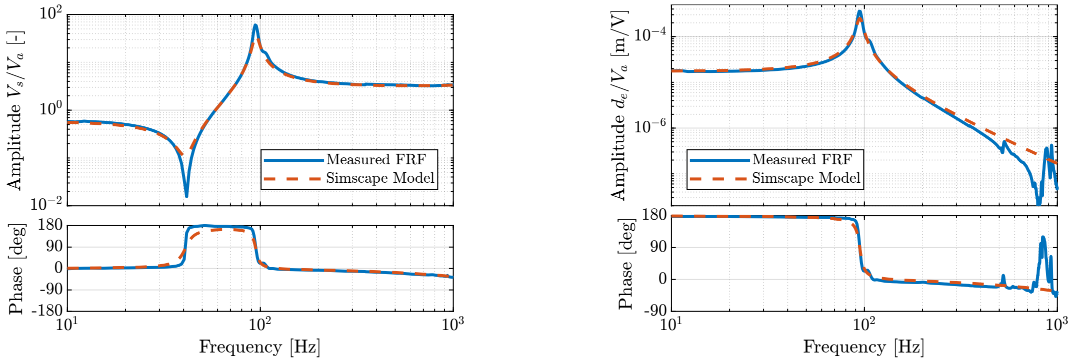


Figure 3: Schematic of the test bench used.

Depending on the application, one can draw advantage of the fact that the APAs (the trapezoïd in Fig. 3) consist of 3 piezoelectric stacks in series. To obtain information on the compression/extension of the whole APA, one piezo stack is used as a force sensor, and 2 stacks as force actuator by wiring them separately (cf. Fig. 3 and technique from [6]).

[2] Specifications APA300ML: `https://www.cedrat-technologies.com/fileadmin/datasheets/APA300ML.pdf` (last accessed 26/3/2021)



(a) FRF: from actuator voltage to sensor voltage.

(b) FRF: from actuator voltage to displacement.

Figure 4: Frequency response functions (FRF) of experimental results in comparison with simulations using reduced order model from FEA.

In order to measure the dynamics of the APA, a digital to analog converter is used to generate a low pass filtered excitation signal V_a which is applied to the two actuator stacks. The voltage generated by the force sensor stack V_s as well as the vertical displacement d_e measured by the encoder are recorded simultaneously.

Then, two Frequency response Functions (FRF) can be computed:

1. actuator voltage to sensor voltage (Fig. 4a) $V_s/V_a(s)$,
2. actuator voltage to displacement (Fig. 4b) $d_e/V_a(s)$.

The comparison of experimental data (blue line) with the simulation (red dashed line) using the reduced order model reveals sufficient agreement for both FRFs to confirm the use of the model for further dynamical analysis using this procedure.

It is found that the open-loop transfer function from V_a to V_s is very typical for APA [6, Fig. 3]. Therefore, the force sensor stack can be used to actively damp the resonance of the APA at around $f_1 \approx 95\,\text{Hz}$ using a technique called "Integral Force Feedback". This technique does not compromise the high-frequency isolation as compared with passive damping techniques and is used in the concerned project's nano-hexapod [7].

CONCLUSION

Modal reduction of finite element models to a more practical reduced number of DoFs make implementation of flexible bodies of any geometry in multibody models possible. The user can decide to perform the modal reduction to include a desired number of Eigenmodes and frequencies in the reduced order model. The application of this technique for the design of the nano-endstation project was very promising and validated on a test bench.

One limitation regarding the response of the reduced model is the unknown damping. Such damping can however be experimentally estimated if the parts are previously available. Also, the reduction procedure is limited to linear behaviour of FEA models due to the reduction procedure via linear modal analysis.

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