Surrogate Mass Optimization for Helicopter Vibration Tests

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EXTENDED ABSTRACT

1 Introduction

Helicopters are very lightweight and flexible structures, making them prone to vibrations. In product development and production, the simulative and experimental prediction of eigenfrequencies and eigenmodes, especially near the blade passage harmonics, is of great importance to prevent unwanted vibrations that can potentially lead to discomfort for the pilot and passengers or even to the loss of control. The eigenfrequencies can be determined with an experimental modal analysis which is also called ground vibration test in aerospace engineering. A common problem with the experimental test setup is that the coupled multibody system, consisting of the non-rotating airframe and the rotating rotor, behaves differently from the free airframe. Hence, it is not sufficient to consider the free airframe only. It is also not possible, though, to include the rotating rotor in the experimental setup of ground vibration tests.

In industrial practice, the behavior of the coupled system is approximated by coupling surrogate masses to the rotor shaft, see, e.g., [1]. However, the choice of the amount of mass is not trivial and there is no general procedure to determine an adequate surrogate mass. This paper aims to overcome this issue and presents a novel approach for selecting a surrogate mass that optimally approximates a particular eigenmode of the coupled system. Therefore, a reference eigensolution is computed for the multibody system with non-rotating elastic airfame and geometrically stiffened elastic rotor. A surrogate model is constructed by attaching a surrogate mass to the free airframe model. The used numerical models are large industrial finite element models provided by Airbus Helicopters. Their evaluation is numerically expensive. Therefore, the surrogate model is reduced with parametric model order reduction, which enables efficient system evaluations and, hence, optimization of the surrogate model under varying lumped masses. This approach is novel in the field of helicopter dynamics and improves the surrogate modeling for experiments.

2 Methodology

In this work, a surrogate model is optimized with a model fitting approach, i.e, the parameters of the surrogate model are chosen in such a way that they ideally approximate a reference solution. Since in this case no measurements can serve as a reference solution, a reference model is built, which describes the coupled multibody system of the elastic airframe and the elastic rotating rotor based on [2] with fundamentals from [3, 4]. The coupled reference model is visualized in Figure 1.

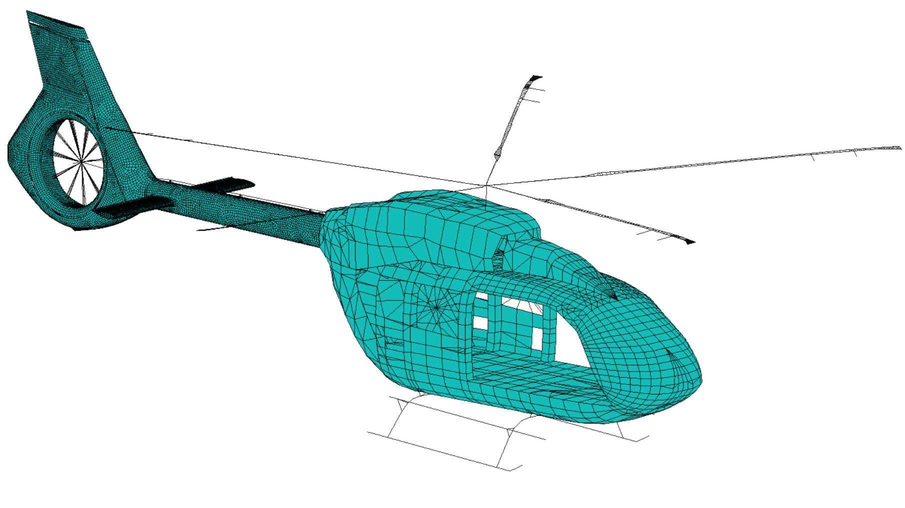

Figure 1: Coupled Finite Element Model of a representative twin engine light helicopter and a five-bladed bearingless main rotor system used at Airbus Helicopters

We then consider the parametric second order surrogate system

$$\begin{aligned} \boldsymbol{M}(m)\ddot{\boldsymbol{q}} + \boldsymbol{D}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} &= \boldsymbol{B}\boldsymbol{u}, \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{q}, \end{aligned} \tag{1}$$

where the parameter m describes a surrogate mass attached to the rotor mast. The matrices $\boldsymbol{M}, \boldsymbol{D}, \boldsymbol{K}, \boldsymbol{B}$ and $\boldsymbol{C}$ are the mass, damping, stiffness, input, and output matrix of the system. The state vector $\boldsymbol{q}$ describes the elastic deformation and the output $\boldsymbol{y}$ consists of selected states at characteristic airframe points. Parametric model order reduction [5, 6] is applied to obtain a system that is efficient to evaluate while maintaining the parameter dependency of the original system including that mass. The optimal surrogate mass is obtained by solving the optimization problem

$$m_{\mathrm{opt}} = \arg\left(\min_{m} \varepsilon(m)\right), \quad m \in [m_{\mathrm{lb}}, m_{\mathrm{ub}}], \quad 0 \leq m_{\mathrm{lb}} \leq m_{\mathrm{ub}} \tag{2}$$

with the cost function

$$\varepsilon(m) = \sum_{i=1}^{n_{\mathrm{f}}} \left[\left(\frac{f_{\mathrm{ref},i} - f_i(m)}{f_{\mathrm{ref},i}} \right)^2 + \left(\frac{1 - \sqrt{\mathrm{MAC}_{ii}(m)}}{\sqrt{\mathrm{MAC}_{ii}(m)}} \right)^2 \right] \tag{3}$$

which is used in [7] to minimize the difference between eigenfrequencies of the reference model $f_{\mathrm{ref},i}$ and eigenfrequencies of the reduced surrogate model $f_i(m)$, and the related mode shapes. The mode shapes are compared with the modal assurance criterion between a reference mode $\boldsymbol{v}_{\mathrm{ref},i}$ and a test mode $\boldsymbol{v}_j(m)$ with

$$\mathrm{MAC}_{ij}(m) = \frac{\left| \boldsymbol{v}_{\mathrm{ref},i}^{\mathrm{H}} \boldsymbol{v}_j(m) \right|^2}{\left(\boldsymbol{v}_{\mathrm{ref},i}^{\mathrm{H}} \boldsymbol{v}_{\mathrm{ref},i} \right) \left(\boldsymbol{v}_j^{\mathrm{H}}(m) \boldsymbol{v}_j(m) \right)}. \tag{4}$$

3 Results

The dependency of the reference solution on the rotational velocity and the dependency of the surrogate model on the lumped mass are shown. A reduced order model which is valid for a large parameter range and shows only very small errors is obtained with moment matching based on Krylov subspaces. It is shown that a single surrogate mass cannot approximate the dynamical behavior of the coupled system over a large frequency range. However, for a given mode shape, the optimal choice of a surrogate mass leads to an improved surrogate model that oscillates with quasi-equal frequencies and shapes compared to the reference. Interestingly, this surrogate does not necessarily equate to the mass of the rotor.

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