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Development of large-scale finite element models for vibroacoustic analysis

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Abstract

The development and analysis of large-scale finite element models is an important step in engineering product development in order to obtain reliable and accurate solutions of the related physical problem. It is a particular challenge when either structures are very large and consist of many single components that are connected at interfaces, or when dynamic analysis is involved where a sufficient fine mesh resolution is required depending on the underlying frequency range.

In this paper we develop implementable and practically useful error measures that are actually applicable for general large-scale problems. For evaluating the required mesh density depending on the actually considered frequency space of the problem, methods from experimental dynamics are employed within a pure computational framework such as the model assurance criterion (MAC-value) and the frequency response assurance criterion (FRAC-value). By employing these criteria it will be shown that the error in frequencies and mode shapes can be easily reduced to a desired level of accuracy.

In order to deal with large-scale problems, standard reduction order methods like the component mode synthesis (CMS) method are employed to drastically reduce the computational effort in the analysis of the full model. To this end, a new practical approach is proposed where the components are not separated at the actual interfaces but at virtual interfaces within the component itself in order to overcome the difficulties of modelling of complex interfaces with (possibly nonlinear) solution behavior. As a result of our approach we found that the definition of virtual interfaces within certain components leads to overall results that are up to 50 % more accurate compared to the classical approach where the CMS interface is located at the actual interfaces of the component.

The methodologies presented in this paper are developed for the vibroacoustic analysis of a 2.5 MW wind turbine at large scale. Despite the special focus on wind turbines, the error estimation procedure presented here is not restricted to applications from structural dynamics. Once a good quality of the discrete models has been established, they can be used to obtain reliable and accurate results also in other large-scale engineering applications. In the considered examples, we find that the procedure is very practical, easy to use and can be easily computed with data from any finite element code.

Keywords: large-scale analysis, error measures, vibroacoustics, wind turbines.

1 Introduction

Finite element analysis has been established as an inherent part of industrial product development. The discrete models should accurately and reliably represent the essential features of the underlying physical problems or processes. The development of such models can become very challenging in the case of large and complex structures, particularly when simulating the dynamic response for a wide range of driving frequencies.

The methodologies presented in this paper are developed for the vibroacoustic analysis of a 2.5 MW wind turbine at large scale. The overall goal is to model and identify the acoustic transfer paths from vibrational sources, like the gear box, to radiating components of the turbine, like the blades or the nacelle cover. From this a further goal is to find efficient design measures to reduce the radiation of tonal noise, see Ihlenburg et al. [1] and Zarnekow et al. [2]. Despite the special focus on wind turbines, our approach is general and can be employed in other engineering applications as well where large-scale structures consisting of many components are considered.

Theoretically well investigated error estimation procedures are available towards the goal of obtaining reliable and accurate numerical solutions. However, a major drawback of these methods is that, in essence, error bounds are either guaranteed but, in practice for complex problems, hardly computable or they are computable but not guaranteed, see Grätsch and Bathe [3]. Here, we develop implementable and practically useful error measures that are actually applicable for general large-scale problems. For evaluating the required mesh density depending on the actually considered frequency space of the problem, methods from experimental dynamics and computational model updating (CMU) are used such as the model assurance criterion (MAC-value) and the frequency response assurance criterion (FRAC-value), see Allemang [4]. By employing these criteria it will be shown that the error in frequencies and mode shapes can be easily reduced to a desired level of accuracy.

In order to deal with large-scale problems, standard reduction order methods like the component mode synthesis (CMS) method are employed to drastically reduce the computational effort in the analysis of the full model, see Craig and Bampton [5]. To this end, a new practical approach is proposed where the components are not separated at the actual interfaces but at virtual interfaces within the component itself in order to overcome the issue of splitting the model at computationally complicated interfaces like bolt connections.

2 Methods

The large-scale finite element model of the whole wind turbine is developed with a bottom-up approach. At first, each component is modeled separately. In order to assure that the discretization error at component level is sufficiently small, which means that the solution quality of the computation is high, some practical error measures are employed. For each single component several mesh density analyses are performed that originally stemmed from experimental dynamics. The MAC-value is used to compare different finite element meshes with each other, where the reference solution is a so-called overkill solution with an extreme fine mesh resolution. All modes up to 1.5 times the highest frequency of interest for the vibro-acoustic simulation are included in the MAC matrix evaluation. Further, in the same manner, the FRAC-value is employed to ensure the convergence in the frequency response up to the highest frequency of interest.

After having obtained finite element models on the component level that are converged regarding their dynamical behavior, the next step is the assembling of the components where an adequate definition of the interfaces between the components is needed. For this, three different approaches are employed depending on the complexity of the interface and mount: (1) Interfaces, where negligibly small deformations can be assumed, are modeled as rigid connections, as for example between the main shaft and the shrink disc of the planet carrier or at the connection between main bearing and main frame of the drivetrain. (2) For other interfaces such as bearings, mounts or similar connections, stiffness and damping matrices are computed at the interfaces, which account for the related stiffness and damping of the connection. To obtain the 6x6 stiffness matrices in these cases, the nominal load at the operating point is applied in all 6 degrees of freedom in space to obtain the corresponding stiffness as the derivation of the force-displacement curve of the respective bearing or other connecting elements. (3) At interfaces with bolt connections a new virtual interface is introduced. The actual interface, which is computationally rather complicated to model, remains within the submodel with all the features like bolts or other connecting parts.

3 Results

A major result of the present research is the development of a large-scale finite element model with sufficiently fine mesh resolutions according to its needs for subsequent vibroacoustic analyses. As a part of the full model, Figure 1 shows the finite element model of the drivetrain when mounted on the mainframe. The finite element model consists of more than 10 million degrees of freedom which is solved in a broad-frequency range at operational stage in the time and frequency domain.

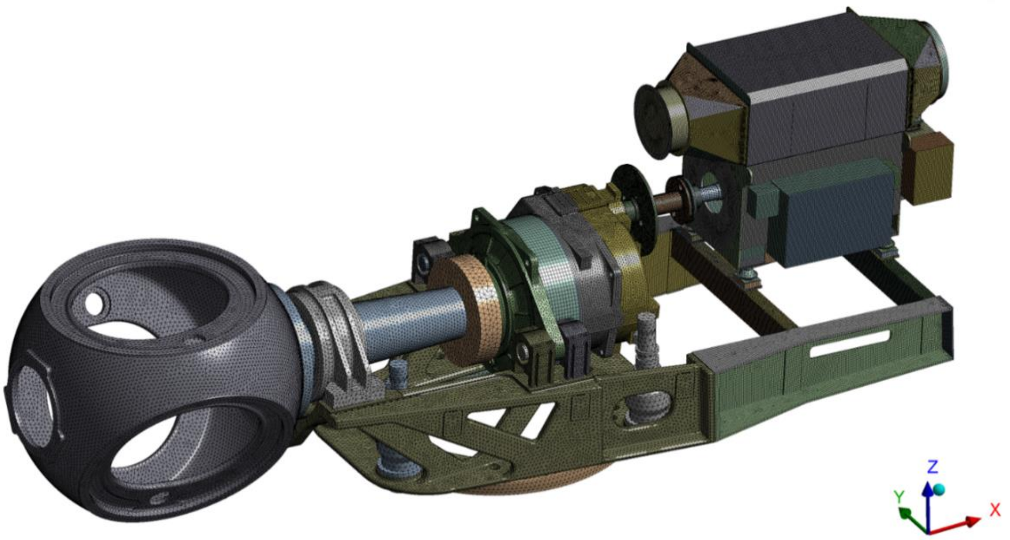

Figure 1: Finite element model of the drivetrain of the wind turbine mounted on mainframe.

For verification of every component the above mentioned MAC- and FRAC-values are employed: Starting from a coarse mesh every component is analyzed and compared to a reference solution employing the MAC-values for the first 200 mode shapes. If the agreement between two mode shapes is larger than 95 % the mesh is successively refined. Further, in the same manner, the FRAC-value is employed to ensure the convergence in the frequency response up to the highest frequency of interest. Figures 2 and 3 show the MAC- respective FRAC-values of the main frame component before and after having found the sufficient fine mesh resolution.

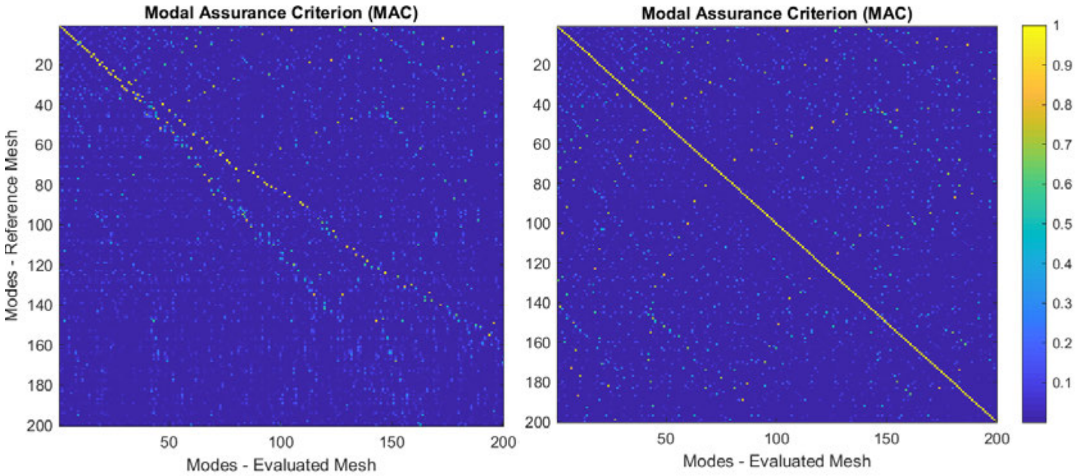

Figure 2: MAC-values of a coarse mesh (left) and a sufficiently fine mesh (right).

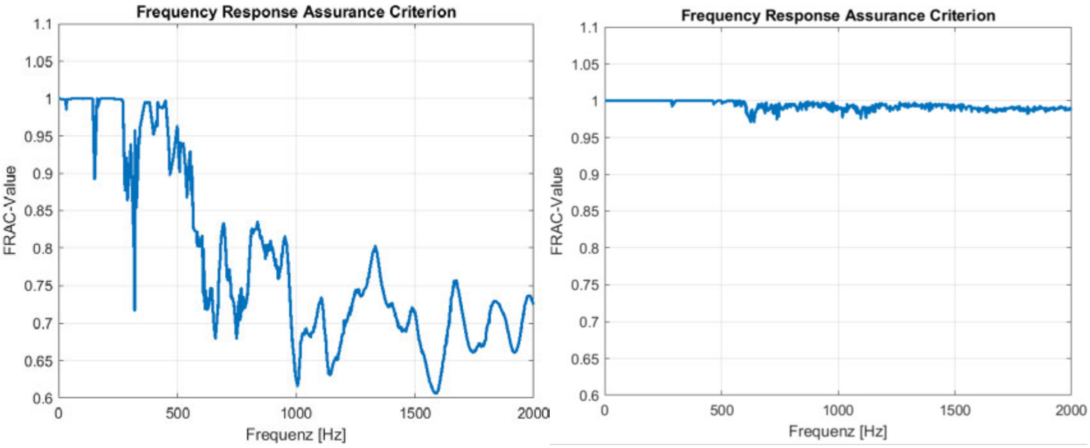

Figure 3: FRAC-values of a coarse mesh (left) and a sufficiently fine mesh (right).

To deal with the computational effort in transfer path analysis (frequency response analysis) of the whole turbine at large scale, the component synthesis method is used. Since the performance of the CMS method strongly depends on the number of degrees of freedom at the interfaces of the single components, the choice of the number and their locations is essential. As a result of our approach we found that the definition of virtual interfaces within certain components leads to overall results that are up to 50 % more accurate compared to the classical approach where the CMS interface is located at the actual interfaces of the component. As an example, in Figure 4 a virtual interface is shown within the main frame.

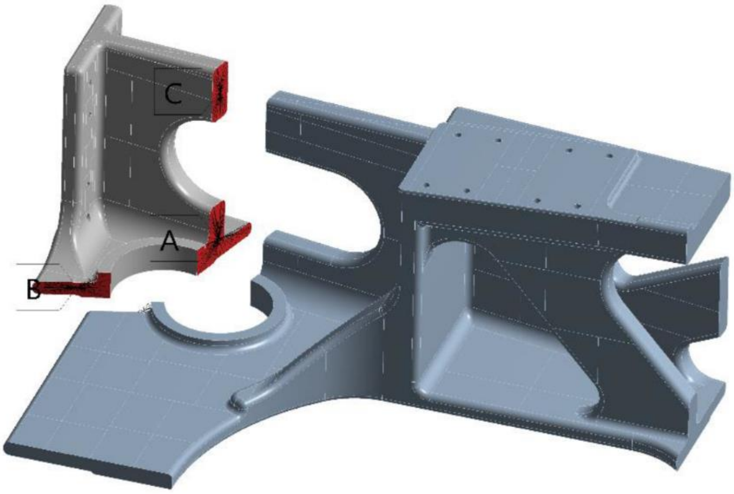

Figure 4: Virtual interface (shown in red) within the main frame in the application of the CMS method.

Results of sound propagation and the actual acoustic transfer analysis are shown at the conference.

4 Conclusions and Contributions

The development of large-scale finite element models for vibroacoustic analysis is presented. This approach includes the development of subsequent finite element models on the component level in a desired level of accuracy. For this, well-known methods of experimental dynamics like MAC- and FRAC-value analysis are adopted and employed within a pure computational framework. The procedure is very practical, easy to use and can be easily computed with data from any finite element code.

The application of reduction order methods like the CMS method has been used in a new fashion in order to overcome the difficulties of modelling of complex interfaces with (possibly nonlinear) solution behavior. The definition of virtual interfaces within the components is proposed leading to a higher solution accuracy instead of using the actual component interfaces.

Using the above mentioned features it is possible to perform vibroacoustic analysis of large-scale finite element models within reasonable computational times. Hence the approach contributes to the goal of first-time-right design in engineering product development.

The error estimation procedure presented here is not restricted to applications from structural dynamics. Once a good quality of the discrete models has been established, they can be used to obtain reliable and accurate results also in other engineering applications.

Acknowledgements

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