Design of test specimen for wind turbines to evaluate passive vibration reduction concepts based on granular materials

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Introduction

Wind energy is a major renewable energy source with the potential to meet the challenges faced in today's world. With the increasing attention on carbon-neutral energy production, wind turbines offer an effective way to generate clean electricity. One of the major goals of the German government is to achieve an 80 - 90% reduction in greenhouse gas emissions by 2050. The result is a rapid development of onshore wind farms, which also have several disadvantages such as: structural vibration, sound emission and visual impact, hindering its global utilization. Among these, the sound emission is one of the major barriers for widespread application of onshore wind turbines and it can result in strong regulatory penalties.

The vibration behavior of the generator, as one typical sound source is caused mainly by the electromagnetic interactions between the spinning poles and the stator. Additionally, the wind turbine blades, as sound radiating surfaces, are targeted in the current contribution. The general purpose is to present a passive vibration reduction concept, which is based on the high damping properties of granular materials. The movement of granular material in the cavity and collision with each other as well as the walls lead to friction and result in a reduction of the vibration amplitudes. Particle dampers have many advantages: they are suitable for harsh environment, have low cost and work over wide temperature and frequency ranges. The exceptional damping properties of granular materials were introduced previously in the work of Duvigneau et al. [1] for automotive applications. In following investigations, Koch et al. [3] show that soft particles, like granular rubber, have a larger damping effect than stiffer particles, like sand, glass and corundum.

In the ongoing studies different types of granular fillings will be examined with respect to their efficiency in reducing the vibration amplitudes of the structure while being as light as possible in order to design a lightweight solution, which increases the overall mass of the wind turbine marginally. For the experimental purpose in the laboratory, small-scaled replica inspired by the original configuration are used as representing geometries for the wind turbine generator and the blades. To evaluate in advance different design configurations with respect to their vibroacoustic behavior in order to meet the behavior of the originally scaled wind turbine components, a series of numerical simulations based on finite element method is performed. One of the design configurations for the wind turbine blade test specimen can be seen in Fig. 1. The constraints and the challenges of the test specimen manufacturing process were also considered during creation of the the finite element model. In this study honeycomb-sandwich-like structures are employed. They consist of several small cavities, which are very useful to optimize the distribution of the granular filling [2].

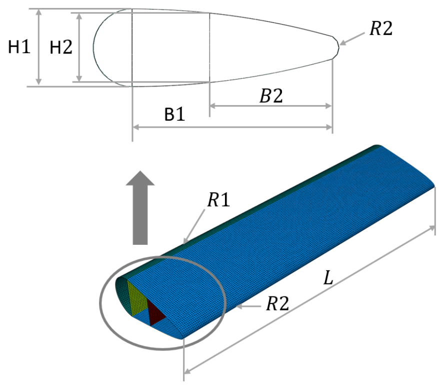

Figure 1: Finite element model of a wind turbine blade section with variable parameters.

Test specimen design

To evaluate different design configurations of the test specimen representing the wind turbine blades and the generator with respect to their vibroacoustic behavior, a modal analysis of each setup was performed. In this context representative vibroacoustic behavior means that a similar number of eigenfrequencies can be found in the frequency region from 0-300 Hz.

Blade design

Due to high specific bending stiffness and lightweight properties of sandwich structures, they are widely used in wind turbine blade design. The idea of this contribution is to replace the original sandwich core by honeycomb-like-structures, as Koch et al. [2] have successfully shown the potential of partial fillings of such a honeycomb structure by granular materials for an oil pan bottom. To study different design configurations for the wind turbine blade test specimens, a small section of an originally scaled wind turbine blade is considered and then a series of modal analyses is performed using the commercial FE software package ABAQUS.

The design of wind turbine blade test specimen is considered as a sandwich structure, which consists of two thin face sheets attached to both sides of a lightweight core, see Fig. 2.

Two different core profiles are examined in this study, see Fig. 3. The diameter of the tube, $\Phi = 8$ mm, is considered to be fixed for all computations because of the manufacturer's limits. All the six sides a of the honeycomb cell are considered to be the same and two different values for a are considered in this study, namely: $a = 4$ mm and 5 mm. The diameter d of the hexagonal cell is computed as: $d = 2 \cdot a$.

For meshing the sandwich plates, quadrilateral shell elements with quadratic shape functions are used, which are beneficial for the analysis of composite and sandwich structures. The Reissner-Mindlin shell theory is used to obtain the solution. The tubus core sandwich plate is fixed on one of the shorter edges. Because of the manufacturer's limitation, it is only possible to design a test specimen with a maximum length of 500 mm length. The length of the tubus core sandwich structure is determined according to the number of cells (diameter 8 mm) and remains the same, $l_p = 496$ mm for all computations in order to keep the length as big as possible and achieve the eigenfrequency as low as possible. The aim is to obtain as many eigenmodes below 300 Hz as possible to imitate the original scaled wind turbine blade behavior. Three different widths and core heights for the sandwich structure with tubus core are evaluated, see Tab. 1. In the following most of the geometry parameters are expressed in relation to the value h_{c_0} due to confidential reasons.

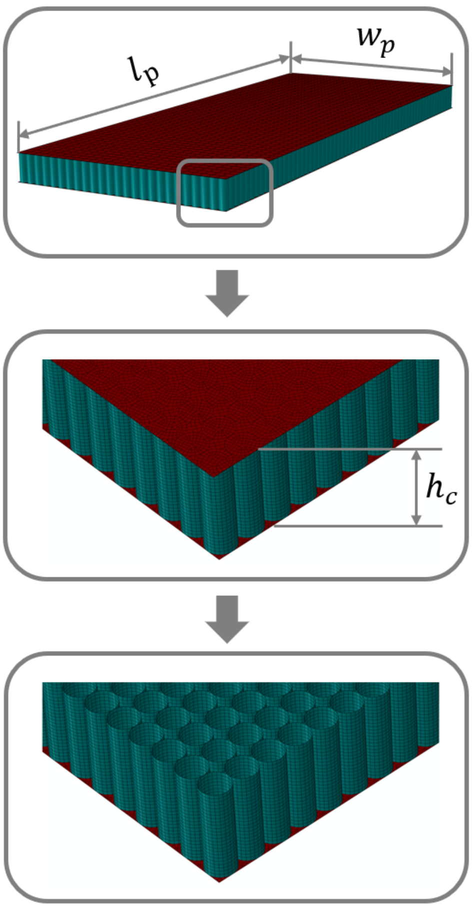

Figure 2: Sandwich structure for the wind turbine blade test specimen, which consists of two thin face sheets attached to both sides of a tubus core.

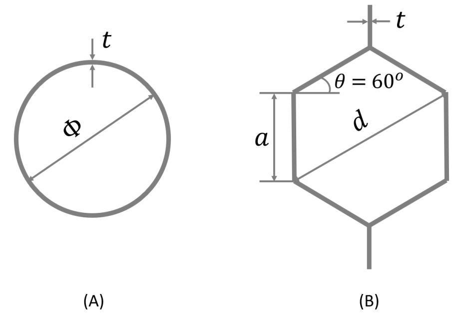

Figure 3: Profile geometry of the sandwich core. (A): Tube profile with thickness t and diameter Φ. (B): Honeycomb cell geometry with edge length a, diameter d and thickness t.

Table 1: Dimension of the tubus core sandwich plate

Length (l_p)	Width (w_p)	Core height (h_c)
[mm]	[mm]	[mm]
496	$12 \cdot h_{c_0}$	$1.0 \cdot h_{c_0}$
		$2.5 \cdot h_{c_0}$
		$3.8 \cdot h_{c_0}$
	$20 \cdot h_{c_0}$	$1.0 \cdot h_{c_0}$
		$2.5 \cdot h_{c_0}$
		$3.8 \cdot h_{c_0}$
	$35 \cdot h_{c_0}$	$1.0 \cdot h_{c_0}$
		$2.5 \cdot h_{c_0}$
		$3.8 \cdot h_{c_0}$

Three different tubus core thicknesses are investigated, namely: $t = 1\,\text{mm}, 0.5\,\text{mm}$ and $0.2\,\text{mm}$. Three different materials are used for the sandwich core in this study, namely: Polypropylene (PP), Polycarbonate (PC) and Aluminum. The material properties are given in Tab. 2. Polypropylene and Polycarbonate are used because they are extremely light and have high tensile strength. Furthermore, they are corrosion and moisture resistant and also reduce the sound emission and vibrations in the structure, as their material damping is typically higher than that of metals. Aluminum is used as a reference material. However, only non-metallic materials are possible for wind turbine blades due to lightning safety requirements. The executed study showed that the use of PP and PC results in almost the same behavior, as the ratio of Young's modulus and density remains similar.

Table 2: Material properties of the sandwich plates

Material	Young's Modulus	Density	Poisson's Ratio
	$[\frac{\text{N}}{\text{m}^2}]$	$[\frac{\text{kg}}{\text{m}^3}]$	[-]
Aluminum	$6.4 \cdot 10^{10}$	2700	0.33
Poly-propylene	$4.75 \cdot 10^{7}$	60	0.40
	$1.05 \cdot 10^{8}$	120	
Poly-carbonate	$1.00 \cdot 10^{9}$	280	0.25
	$2.70 \cdot 10^{9}$		
	$6.00 \cdot 10^{9}$		
Steel	$2.1 \cdot 10^{11}$	7850	0.30

For modal analysis of the honeycomb sandwich plates two scenarios are investigated. In the first scenario, free-free boundary conditions are modeled, while in the second case the honeycomb plate is clamped on one of the shorter edges. The length and width of the honeycomb sandwich plate is, $l_p = 500$ mm and $w_p = 35 \cdot h_{c_0}$, which is possible due to the cell diameter of the honeycombs of $d = 10$ mm. For the honeycomb sandwich plate two different parameters are investigated, namely: diameter and height of the honeycomb cells. The influence of three different diameters of the honeycomb core, on natural frequencies is studied. Additionally, three different core heights are investigated in this study. Meanwhile the thickness of the honeycomb core is 1 mm and the thickness of the top and bottom face sheets of the plate are 2 mm each. Two different types of materials are used for the modal analysis, aluminum and polycarbonate (PC). The material properties are given in Tab. 2.

Results of the study for the blade design

It has been found that the two different core profiles do not show a strong influence on eigenmodes and eigenfrequencies. Moreover, reducing the width of tubus core sandwich plate from $35 \cdot h_{c_0}$ to $12 \cdot h_{c_0}$ shows a small deviation of $2-3\%$ in eigenfrequencies. This observation is reasonable as the width contributes linearly to both the resulting stiffness and mass. Varying the thickness of the tubus core shows no significant effects on eigenfrequencies. Increasing the height h_c of the tubus core and honeycomb plate makes the structure stiffer, which results in roughly 2% increase of the eigenfrequencies for the investigated cases. Further, in all the cases the eigenmodes of the structure remain qualitatively the same, see Fig. 4, in which only the bending modes are plotted (mode number 1, 4 and 6), however torsion modes are also present.

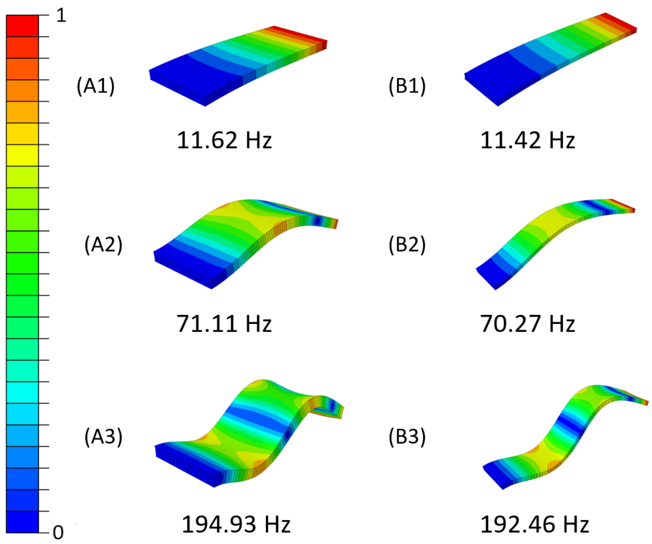

Figure 4: (A1)-(A3): Eigenmodes of the tubus core structure of dimensions, length $l_p = 496$ mm, width $w_p = 20 \cdot h_{c_0}$ and height $h_c = 0.25 \cdot h_{c_0}$. (B1) - (B3): Eigenmodes of the tubus core structure of dimensions, length $l_p = 496$ mm, width $w_p = 12 \cdot h_{c_0}$ and core height $h_c = h_{c_0}$.

In contrast to the clamped configuration, for the honeycomb sandwich plates with free-free boundary conditions the influence of the honeycomb cell diameter on eigenfrequencies is negligible. In Fig. 5 the first six non-zero eigenmodes for an unconstrained plate are plotted. The eigenmodes of simply supported plates are similar to Fig. 4.

After investigating the unconstrained honeycomb plate and one edge fixed honeycomb as well as tubus core plate, it can be concluded that the sandwich plate, which is fixed on one of the shorter edges resembles best the behavior of the originally scaled wind turbine blade. Therefore, this test specimen configuration will be considered for the experimental investigations.

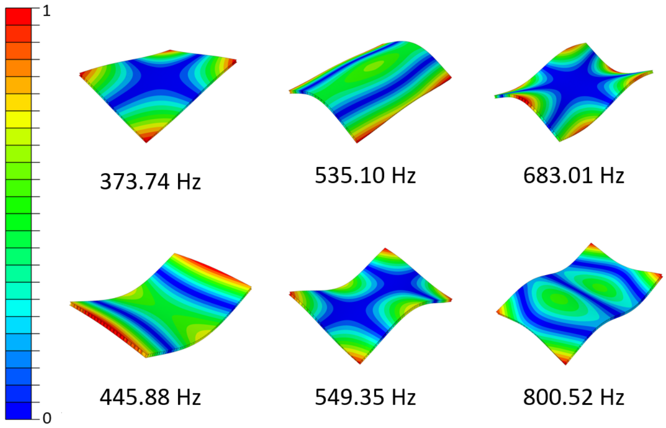

Figure 5: First six non-zero eigenmodes of the unconstrained honeycomb sandwich plate.

Generator design

The generator is one typical sound source in wind turbines. The electromagnetic interaction between stator and spinning poles causes mechanical vibrations in the generator. In this work the stator of an annular generator is investigated, which consists of a big ring and several arms, which are connected to the ring and carry the whole structure. Manufacturing the exact replica of this stator for laboratory purpose is not possible because scaling the original dimension make the cavity dimensions, used for the filling with granular materials, so small that it become impossible to manufacture. Therefore, it is necessary to create simple profiles by taking a small section of the original wind turbine generator and scale it, which can reproduce the behavior of the originally scaled wind turbine generator. For this purpose, again a modal analysis is performed on different profiles, such as I-profile, L-profile and T-profile. Here, the aim is to obtain the same number of eigenmodes below 300 Hz as in the case of the original generator. Finally, it can be concluded that the T-profile resembles the chosen stator section of an annular generator in a very close manner. To analyze the vibroacoustic behavior of the T-profile, a free-free modal analysis is performed. The dimensions of the T-profile can be seen in Fig. 6. Apart from original dimensions, two scaling factors are also investigated. In this context scaling means that all the dimensions including the thickness are scaled by the corresponding factors. Steel is used for the modal analysis as this is also the case in the original scaled generator. The material properties of the steel can be seen in Tab. 2. A parameter study is carried out to analyze the effect of the parameters shown in Tab. 3 and Fig. 6 on the resulting eigenfrequencies and eigenmodes. The values of c_G and e_G are $1.4 \cdot a_G$ and $2 \cdot a_G$, respectively.

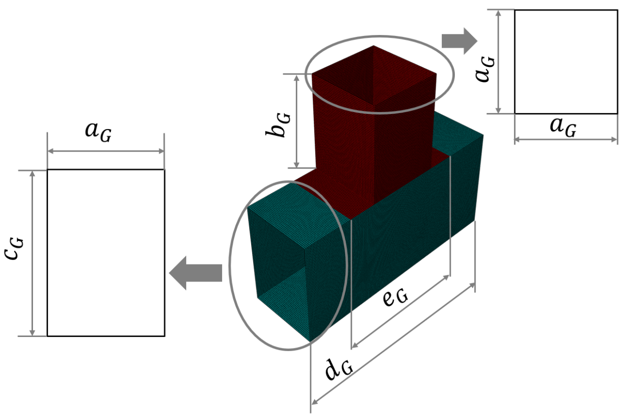

Figure 6: Design parameters of the T-profile of the generator test specimen.

Table 3: Variation of the parameters d_G and b_G

	d_G [mm]	b_G [mm]
Fig. 7 (a)	500	200
Fig. 7 (b)	340	
Fig. 7 (c)	200	
Fig. 7 (d)	500	250
Fig. 7 (e)	340	
Fig. 7 (f)	200	

Results of the study for the generator design

The scaling factor shows almost no effect on the eigenmodes of the structure. The eigenfrequencies decreases with the scaling factor, which is expected due to the cubic influence of the thickness on the plate stiffness. When the parameter b_G is kept fixed, i.e 200 mm in one case and 250 mm in the second case, and the parameter d_G is decreased from 500 mm to 200 mm, the structure becomes less stiffer, see Fig. 7. Nevertheless, the eigenfrequencies are in the same range and the eigenmodes remain almost the same in all the cases. Therefore, a configuration is chosen which has advantages due to the handling in the experiments.

Summary

In this work, the design process of test specimen for a wind turbine to evaluate a passive vibration reduction concept based on granular materials is presented. To develop the test specimens, numerical simulations based on the finite element method are executed. For the wind turbine blade specimen several modal analyses on sand-

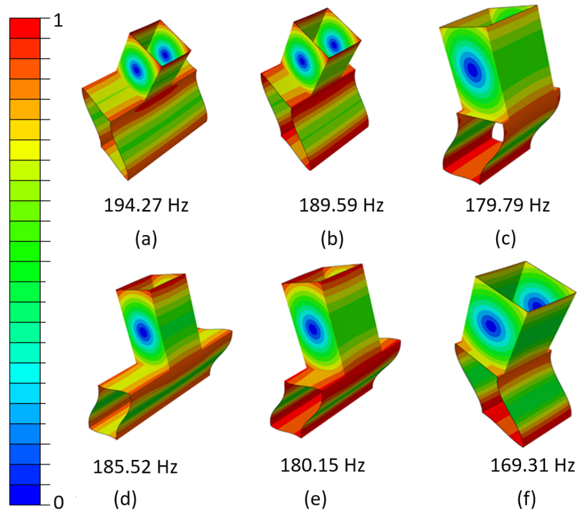

Figure 7: First non-zero eigenmodes of the generator test specimen for different length, width and height (see Tab. 3).

wich structures are performed. Two different sandwich core profiles are analyzed showing negligible effects on eigenmodes and eigenfrequencies. Moreover, the eigenfrequencies remain almost same with decreasing thickness of the cell walls. Increasing width of the sandwich structures makes the structure slightly stiffer (increase of eigenfrequencies $2\% - 3\%$). The sandwich plate, clamped on one of the shorter edges, is favorable for experimental investigation as it resembles the behavior of the original wind turbine blades best. For the generator test specimen, a scaled T-profile is chosen as lab specimen. In the next step the vibroacoustic behavior of the test specimens with different filling materials and distributions will be evaluated with the help of a laser scanning vibrometer in order to determine an optimal configuration due to resulting sound reduction and overall mass.

Acknowledgements

The presented work is part of the joint project DampedWEA (Innovative concepts for vibration and sound reduction of gearless wind turbines), which is financially supported by the Federal Ministry for Economic Affairs and Energy. The support is gratefully acknowledged.

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