ENDLESS FIBRE-REINFORCED COMPOSITE-METAL-IMPELLER: INVESTIGATION AND COMPARISON OF THE DAMPING BEHAVIOUR

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SUMMARY

The mode shapes and loss factors of a modular carbon fibre-reinforced plastic (CFRP) composite impeller were determined experimentally and virtually at the component and the impeller level from the validation pyramid. The results are compared with those of investigations on steel reference models and structures. Good correlations were found between the results of the simulation and the experiment of the metallic structures. The similarities were much less marked for the CFRP parts. The damping behaviour of the CFRP impeller is significantly larger compared to steel, mainly due to the modular design.

INTRODUCTION

The performance and efficiency of future and existing blowers can be improved by using new types of high-performance impellers made of fibre composite materials [1, 2] Composites have excellent density related mechanical properties allowing to significantly increasing the rotational speed. Reduced mass of the impellers, especially the lower inertia, allows faster reactions to variable speeds and uses less energy. Composites enable variable designs of the blades, which leads to flow-optimized cross-sections improving the efficiency and may reduce noise [2-4]. Furthermore, the layered structure of such impellers provides a basis for the integration of sensors for component monitoring and data generation [5, 6]. Due to the better damping capacity of the polymer matrix of the composite, compared to metals, the use of fibre-reinforced materials can enable advantages in operation of such impellers [9-11].

Due to the large number of adjustable parameters, the special knowledge that is required for their design as well as the high expenses and risks for the development and production of integral rotors, these are currently only niche products. Therefore, in cooperation with the *Forschungsvereinigung für Luft- und Trocknungstechnik* (FLT), a modular design of a high-performance impeller was developed at the TU Dresden, whose functionality was presented in a first FAN paper [7] (acc. figure 1).

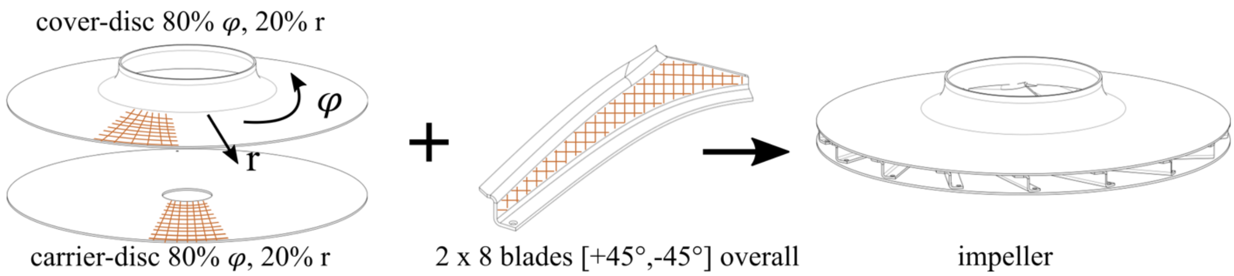


Figure 1: design of the modular composite-metal radial-impeller with material orientations (left) and assembled impeller (right) [6]

Due to the various adjustable parameters, numerical analyses are established for the development of fibre composite components. The decisive factor here is a sufficient accuracy of the virtual models in relation to the physical models. This is often achieved by a combined approach of virtual models and physical experiments at different levels of the test pyramid [8]. However, since dynamic properties such as natural frequencies and their corresponding modes depends on the material in combination with the geometry, a transferability of the results from a lower to a higher level need to be investigated.

MATERIALS AND METHODS

To investigate the dynamic behaviour, a modal analysis with no rotational speed is performed according to the test pyramid. The first investigations were virtual experiments on a steel reference carrier-disc and the new designed one from CFRP. Then followed physical experiments on manufactured discs (step 2) and a comparison of the results with those of step 1. In the third step the virtual experiment were performed with a model of the steel reference impeller (a manufactured reference wasn't available) and in step 4 a physical experiment with a manufactured CFRP impeller. Finally, the results of both tests of the impellers are also compared (acc. figure 2).

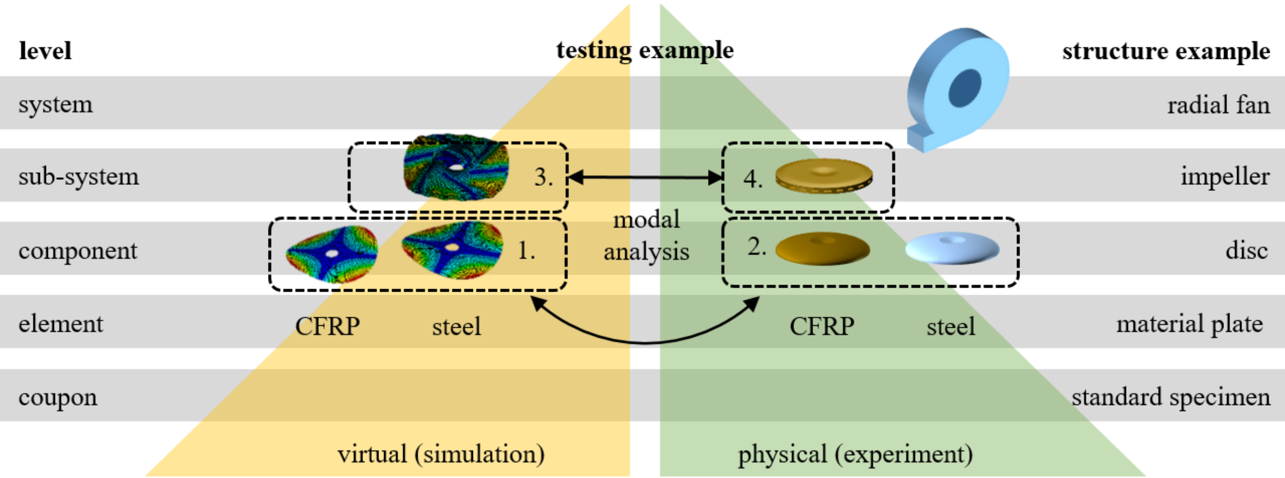


Figure 2: Validation pyramid – specimen locations

During the evaluation of the physical experiments of the CFRP components, the loss factors were also determined and compared to literature values for steel and epoxy resin.

The investigated impeller made of CFRP has a diameter of 1010 mm and weighs about 35 kg. It consists of a carrier disc, a cover disc and 8 small and large blades (acc. figure 1). All parts were manufactured from prepreg in a manual lay-up process and then bonded to assemble an impeller. The details of the manufacturing process are summarized in [7] (acc. figure 3).

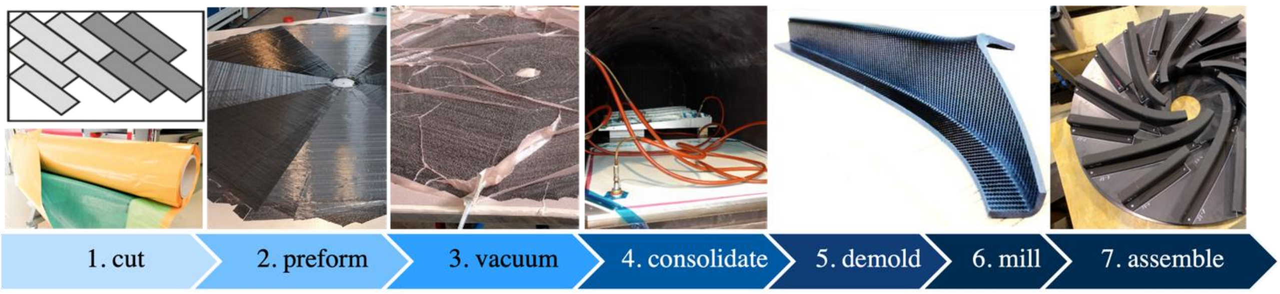


Figure 3: *Manufacturing process of the composite parts and assembling*

The carrier disc was selected as the component-level specimen (acc. Figure 2). It has the same diameter as the impeller and a target thickness of 5 mm. The manufactured thickness due to thicker single plies of the prepreg was 5.84 mm. The steel disc have also a diameter of 1010 mm and a thickness of 5 mm.

The experimental determination of Natural frequencies and modes is performed with the Simcenter Testlab from SIEMENS. For this purpose, a wireframe model of the specimen is created in the software and the position of their nodes are transferred to the samples (see example in Figure 4). Then, the specimens are suspended as freely as possible. Subsequently, accelerations caused by striking the nodes with a modal hammer are measured with an acceleration sensor fixed to the sample at a constant position for all measurements (moving hammer technique). The measured transfer functions for each node are added up to a so-called sum function. Peaks in the sum function represent the Natural frequencies. The software calculates the modal parameters (Natural frequency, modal loss factor and mode shape) for each selected peak.

The numerical modal analyses were performed with the Software system ANSYS 18.2. For this purpose, volume models of the specimens were created. The mesh for the fibre composite parts is layered according to the layer structure, so that the direction-dependent material properties could be assigned to the individual layers. They can be found in [7]. The mesh for the steel specimens was created with one element in the thickness direction. No bearing boundary conditions were specified to replicate the free suspension from the experiment. The simulation was then performed and the first 10 natural frequencies with their associated mode shapes were determined.

EXPERIMENTS AND RESULTS

On the basis of the Eigen modes determined in the simulation of the steel disc, the number of nodes of the wireframe models on the outer diameter was set to 16 so that it is similar to the pattern of the blades from the impeller and mode shapes with many maxima on the outer edge (see tab. 1 eigenmode no. 9) can be identified. The wireframe model of the discs consists of 64 nodes and the model from the impeller is composed of 128 nodes. The suspension is realized with two thin polymer cords. This minimizes the influence of external forces. A thicker blue rope was added as a loose loop to protect the specimens from damage in case one of the suspension cords fails. The individual points are excited one after the other with the help of a modal hammer and the vibration response is recorded with the help of acceleration sensors. For each measuring point, five independent measurements are averaged. Figure 4 shows the acceleration sensor for measuring the vibration (small picture) and the experimental setup for the tests with the composite impeller (big picture).

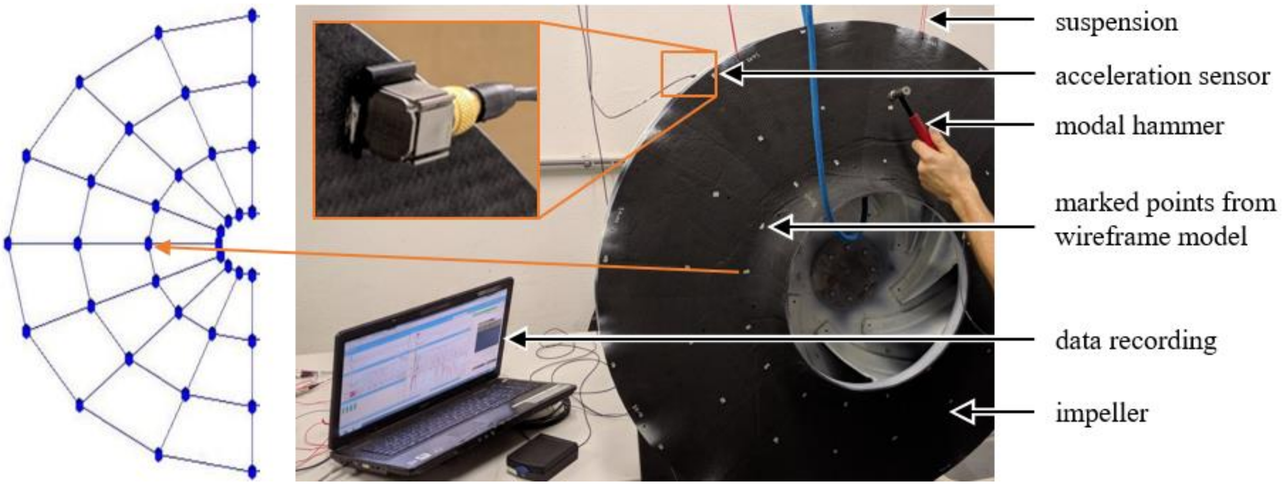
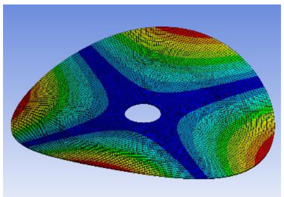
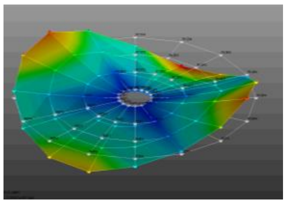
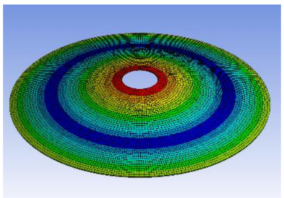
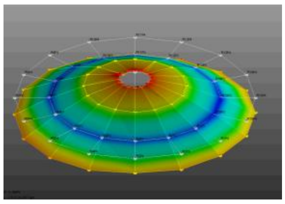
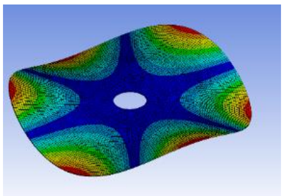
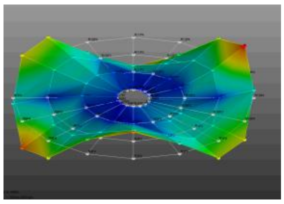
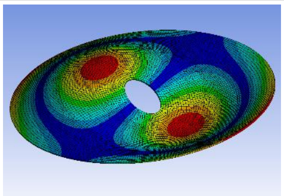
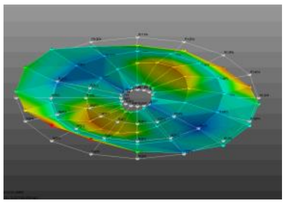
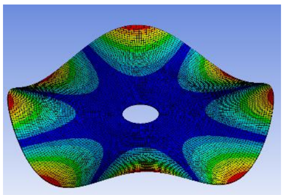
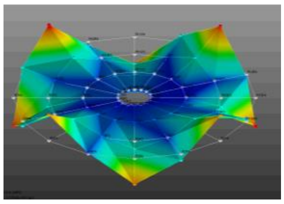
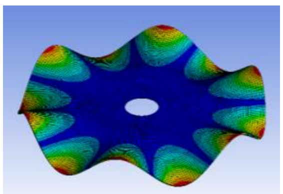


Figure 4: Experimental modal analysis: wireframe model (left) and setup (right)

The vibration response measured via the sensors is added up with a sum function. The natural frequencies of the component can be identified by a sharp increase in the level of the vibration. A programmed algorithm does the evaluation of the recording. Both the modal hammer and the sensor data are stored directly in the wireframe model, which then allows a vibration model of the impeller to be created.

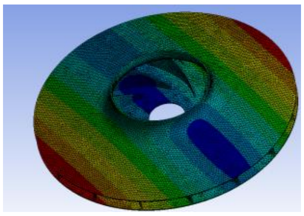
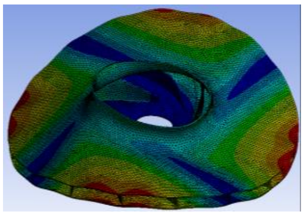
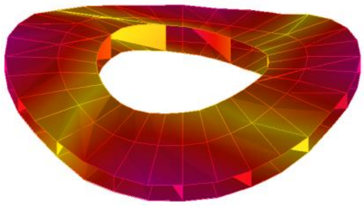
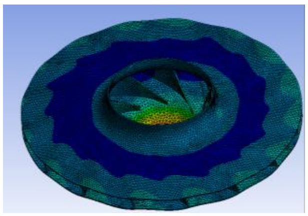
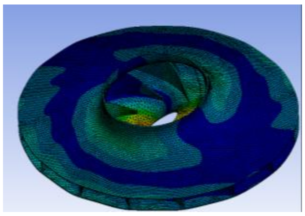
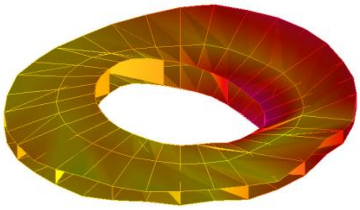
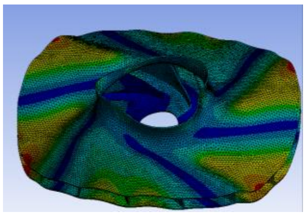
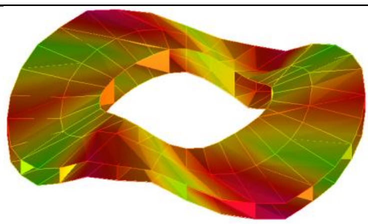
Table 1 shows the results from the investigated discs. The first five mode shapes and the corresponding natural frequencies of the simulation from the steel disc were displayed (mode shapes of the same shape, which are only rotated but at the same frequency, were not considered in the sequence). The same modes were then searched for in the results of the CFRP disc and their natural frequencies were entered in the table in the fourth column. The frequencies and shapes of the experimentally determined results were also entered in the same way.

Table 1: Results of the investigations on the discs

Nr. of mode shape	Steel simulation		CFRP simulation	Steel experiment	CFRP experiment	
	mode shape	natural frequency [Hz]	natural frequency @ similar mode [Hz]	natural frequency @ similar mode [Hz]	similar mode shape	natural frequency @ similar mode [Hz]
1		25,0	25,9	27,6		60,2
2		41,1	54,4	38,0		71,7
3		59,2	60,5	62,0		67,1
4		96,4	94,8	93,0		127,1
5		103,9	88,4	107,0		118,6
9		225,0				

Based on the good match between simulation and experiment of the steel disc, simulation results of the reference steel impeller were considered to have sufficient accuracy, so that a comparison with the experimental results from the CFRP impeller appears permissible. The results of the tests were presented in table 2 in the same way like these from the discs.

Table 2: Results of the investigations on the impellers

Nr. of mode shape	Steel simulation		CFRP experiment	
	mode shape	natural frequency [Hz]	similar mode shape	natural frequency @ similar mode [Hz]
1		6,1	not identified	
2		252,8		505,0
3		352,8	not identified	
4		378,0		1066,5
5		422,0		688,5

In addition to the determination of the natural frequencies and mode shapes, the loss factors of the experimentally investigated specimens were also determined by the software during the processing of the measured values (based on the frequencies at 3 dB bandwidth spacing). In Figure 5 the results are shown in comparison to material properties of steel and epoxy resin, found in [12].

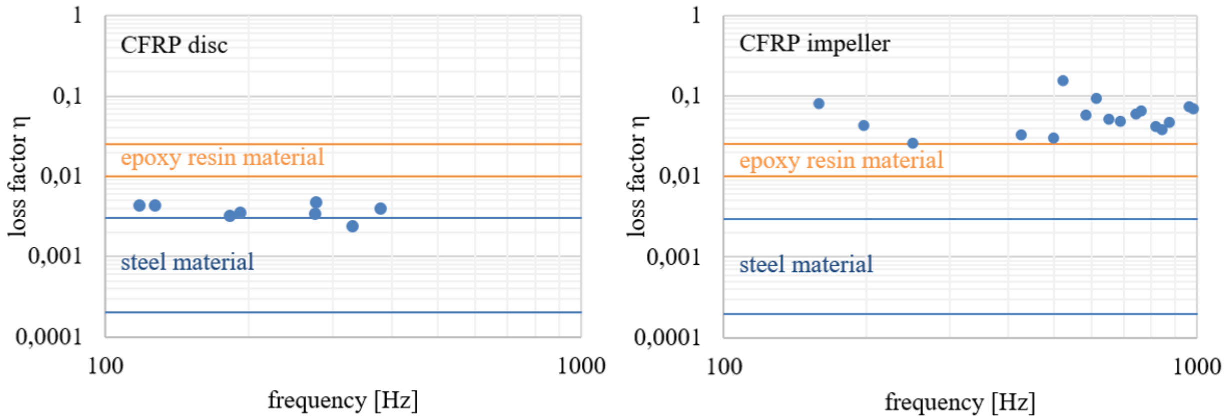


Figure 5: damping behaviour of the CFRP structures at different frequencies in comparison to material properties [12]

DISCUSSION

In the first comparison between the results of the disc's simulations, both the mode shapes and their natural frequencies are very similar despite the different materials (acc. table 1 column 3 and 4). One reason for this may be the identical thicknesses of 5 mm of both models. Another possibility may lie in the high proportion (80 %) of ideally radially oriented reinforcement of the CFRP disc, which have a homogeneous structure in the directions of the dominant bending shapes, comparable to metallic materials.

The comparison of the results of simulation and experiment of the steel disc shows almost identical natural frequencies with the same mode shapes (acc. table 1 column 3 and 5). Reasons for the very good agreement may be the identical dimensions of the model and the manufactured disc and also the homogeneous material.

The mode shapes of the experimental modal analysis of the CFRP disc could also be assigned to similar shapes in the simulation of the metallic disc. However, the corresponding natural frequencies deviate and are also in a different order than the modes (acc. table 1 column 3, 4 and 7). Deviations can also be seen in comparison to the simulation of the CFRP disc. This may be due to the greater thickness of the manufactured disc (5 mm in the model, 5.8 mm in the fabricated disc), or also to inhomogeneity's in the ply structure, since the fibres in the blank of standard commercial available semi-finished materials do not correspond to the curvature of the disc and thus no ideal radial reinforcement can be achieved. The blanks used tend to be triangular, so that the fibre pattern corresponds more to a polygon instead of a circle (acc. Fig. 6).

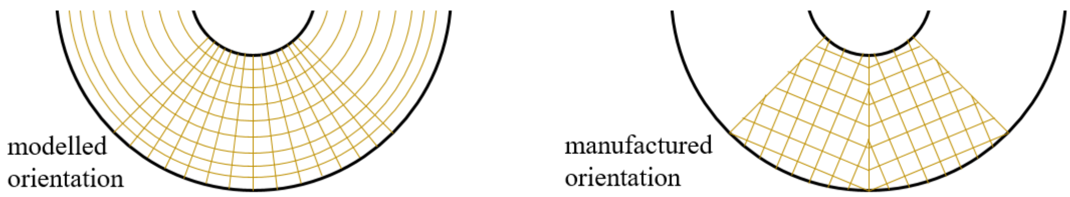


Figure 6: different orientation of fibres in simulation (left) and experiment (right)

The mode shapes determined in the simulation of the steel impeller are similar to those of the simulation of the steel disc, but an exact assignment has not been made. The natural frequencies determined are significantly higher than those of the disc. This also applies to the comparison of the experiments with disc and impeller made of CFRP. For example, the first mode shape of the discs is comparable to the second mode of the impeller. The natural frequency of the CFRP disc is about twice that of the steel disc. This ratio remains roughly the same for the impellers, except that the frequencies here are almost 10 times as high. This can be explained by the stiffer geometry of the impellers, each consisting of two discs with webs in the shape of the blades.

Due to the good agreement between the simulation and the experiment of the steel disc, a similar relationship to an experiment on the steel impeller is assumed. Therefore, the results between the simulation of the steel impeller and the experiment of the CFRP impeller can be compared. Despite the similar shape, only a few matching modes could be found. Their frequencies are higher in the CFRP impeller and also in a different order.

The loss factors of the disc made of CFRP are higher than those of steel and lower than those of epoxy resin. This is in line with expectations, as the resin is only proportionally contained in the composite and the fibres have a similarly low damping as steel. The loss factors of the impeller are predominantly above those of epoxy resin. One reason for this could be that it is not a monolithic structure like the disc. The impeller is made of several components bonded together with an elastic adhesive (3M DP490). Although the adhesive layer thickness is relatively low (0.2 mm on average, adjusted by admixed glass beads), it probably ensures a certain degree of decoupling.

CONCLUSION

With the results presented here, the vibration behaviour of a CFRP impeller could be determined on the basis of experimental modal analysis. Similar mode shapes of the components could be identified across all tests. However, the degree of similarity was very different. In the investigations of the steel discs, there were many matches between the simulation and the experiment in terms of mode shapes and frequencies. Compared to the simulation results of the steel impeller, many similar modes were found, but at significantly higher frequencies. From the results, it can be concluded that the design of these components along the validation pyramid can also largely be carried out virtually and only needs to be checked at a few points by means of an experiment. This reduces the development effort. The results of the CFRP disc examinations show greater deviations. This may be related to the differences between the geometry of the model and the manufactured structures. The deviations concern both the geometry (different thicknesses) and differences in the laminate structure (fibre orientation). One way to improve the accuracy of the simulation is to subsequently adjust the models to the manufactured structures. In the case of the whole impeller, this means partitioning the models of the discs, adapting the element coordinates more precisely to the layer structure in each layer, taking the real layer thickness into account and modelling the joining zone with the adhesive and assigning its correct viscoelastic properties. Here it must be checked whether the effort is justified against the background of the knowledge gained, for example if a structure is produced anyway for mechanical burst tests and the modal analysis is carried out experimentally. When mechanical designing impellers with the help of the validation pyramid, experiments must therefore be carried out more frequently to validate the simulation results. For the consideration of the vibration behaviour, an abstraction over different levels of the validation pyramid does not seem to make sense, as it is difficult to determine correlations due to different geometries. The high loss factors of the CFRP impeller are only partly related to the material, but also to the design and the chosen joining technology (bonding with elastic adhesive). For a good-natured behaviour of blowers and compressors, the use of CFRP impellers can thus bring advantages.

ACKNOWLEDGEMENT

The authors would like to thank the *Forschungsvereinigung für Luft- und Trocknungstechnik* (FLT) for financial support in the LeRaLa project (grant agreement no. 66570) and Moritz von Unold for support in the experimental and numerical work.

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