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Condition monitoring of multi-material lightweight components through a sensitive outer skin using Fiber-Bragg-Grating sensors

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Abstract

Multi-material structures for lightweight applications are continuously gaining increased importance, especially in future industries, such as wind power or electro mobility. Material combinations of metal and fiber reinforced polymer (FRP) composites subjected to high or cyclic loads are critical at the interface. The integration of sensors in multi-material components allows for additional functionalities from needs-based maintenance to continuous condition monitoring and fault detection. In addition, the obtained data even further allows the exploitation of the full potential for lightweight design. Inspired by nature and following the concept of Biological Transformation, the technical approach for the implementation of condition monitoring on multi-material components makes use of the periosteum in the endoskeleton of vertebrates as a bionic model. This concept was adopted for metal-FRP multi-material combinations with the integration of Fiber-Bragg-Grating (FBG) sensors within the FRP. By subjecting components to vibration by external excitation, damages in form of delamination were successfully detected by analyzing the state-dependent natural frequencies of the component. Test specimens were prepared and the influence of various parameters such as frequency, location and direction of the excitation as well as the fixture of the samples during excitation on the natural frequency was investigated. The approach was further demonstrated on the example of a component from the sports industry. The chosen snowboard is expected to fulfill lightweight requirements on the one hand while being exposed to irregular high loads.

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Keywords: Multi-material lightweight design; Sensor integration; Fibre-Bragg-Grating Sensors; Condition Monitoring; Biological Transformation; Fibre-Reinforced Plastics; PBF-LB/M;

1. Introduction

Digital technologies already have significant impact on industrial processes as well as on product development. Sophisticated tools such as artificial intelligence or the progress in secure data communication allow the digital and physical world to be associated to the industrial environment. However, this gain also means an increasing consumption of resources (e.g. energy) which in combination with population growth endangers human welfare. Therefore, sustainable value creation and the maintenance of our living standards was appointed as a central pillar of the UN Sustainable Development Goals [1]. To achieve this goal, new concepts and approaches, which consider on the one hand sustainability along the whole lifecycle of a product and on the other hand ecological, economic and societal aspects, become necessary.

With the concept of Biological Transformation the Fraunhofer-Gesellschaft significantly contributes to a holistic

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transformation process in industry in order to achieve the climate targets using digitalization with simultaneous human-centric value creation [2]. Therefore, materials, structures, principles and organisms from living nature are continuously adopted and applied in technology. The overall goal includes the generation of future solutions for sustainable value creation through the convergence of different disciplines [3–5].

Biological Transformation manifests itself in the following three steps with increasing complexity and multi-disciplinary:

Bio-Inspiration implies the application of principles and processes inspired by nature into technical systems. For example: lightweight construction motivated by structures, which can be found in nature or biomechanics [6, 7]. *Bio-Integration* describes the combination of biological components with technical systems in the industrial context. For example: the substitution of chemical processes by biological ones driven by organisms such as cells or enzymes. *Bio-Interaction* represents the interaction between technical, informational and biological systems [8]. Such so called bio-intelligent systems are characterized by the ability of self-optimization [5, 9].

The approach described in this work is assigned to the stage of Bio-Inspiration and deals with the use of Fiber-Bragg-Grating (FBG) sensors in material combinations of metal and fiber reinforced polymer (FRP) composites. As a bionic role model from nature, the periosteum in the endoskeleton of vertebrates is adopted (Figure 1). The skin surrounding the bone contains nerve cells and, unlike the bone, is sensitive to pain. If damage occurs to the bone, the signal of pain is not created or transmitted by the bone itself, but through its outer skin in form of pain signals. The surrounding skin thus performs sensory tasks and transforms the stimulus signal into an electrical signal for further transfer to the central nervous system, while the bone takes over load carrying functions. In the technical implementation the idea is to have a lightweight metal or wooden structure surrounded by an outer skin of FRP with an integrated FBG sensor for the monitoring tasks.

The current study sets the focus on vibration analysis which implements a new potential condition monitoring technology that allows components to be replaced or serviced only when necessary. Thus, in terms of Biological Transformation, the presented approach contributes to the conservation of resources and the creation of added value.

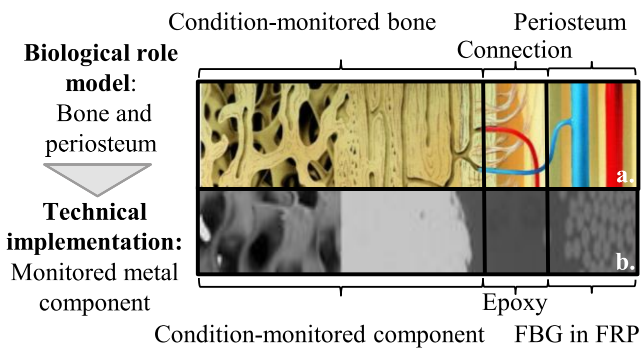

Figure 1: Bio-inspired condition monitoring: a) Bone structure (adapted from [10]), b) Lightweight metal structure with bonded FRP layer and FBG on top

2. Method

2.1. General concept and measurement equipment

FBG sensors have very small diameters of up to 120 µm, are resistant to corrosion as well as electromagnetic interference and require no additional cables for power supply or evaluation [11]. Thus they are very suitable for the integration in the area of FRP within a component for monitoring purposes with low impact regarding surrounding structure and weight. The standard applications for FBG sensors are temperature or strain measurements. But with a theoretical strain sensitivity as small as 1.21 pm/µε these sensors are also suitable for structural health monitoring (SHM) applications by vibration analysis, for which the detection of small strains in very short time intervals is necessary [12]. In addition, the detectable frequency is only limited by the current state of the art of the interrogators (evaluation units), so that the technology can be attributed a lot of further development potential in the future.

One possible implementation of vibration analysis by means of FBG sensors are measuring systems based on the analysis of Lamb waves. Lamb waves are propagating along thin plates and are a combination of longitudinal and transversal waves. Several publications describe the successful detection of cracks and delaminations in test setups made of metal plates in combination with FRP [13–15]. For the emission of waves piezo-ceramic actuators are integrated in the monitored structure, while detection is performed by FBG sensors. Since the propagation of the Lamb waves depends on the mechanical properties of the component, defects can be identified [14]. However, the use of piezo-ceramic actuators requires additional space in the component and peripherals. Moreover, the measuring principle is limited to thin-walled components.

Another method of vibration based SHM systems is modal analysis. It is used to determine the dynamic behavior of a vibrating system and is based on the fact that modal parameters such as natural frequency, mode shape and damping depend on the physical parameters of the structure to be monitored. If a defect, which changes the physical parameters, occurs, this consequently leads to a change in the modal parameters. Amongst all modal parameters, natural frequency is particularly suitable for SHM applications because it provides very accurate results. To generate measurable vibrations, an external excitation of the component is sufficient. Sensors such as piezoelectric vibration sensors can therefore be applied for detection [16].

In order to ensure the least possible impact on the surrounding structure, instead of piezoelectric vibration sensors FBG sensors were chosen for sensor integration. Especially their suitability for defect detection, with focus on delamination, in multi-material components by means of detection and evaluation of natural frequencies was investigated.

Figure 2 gives a schematic overview of the experimental setup and the applied components. Six FBG sensors with a diameter of 125 µm and ten measuring points each were applied. For the FBG sensors different gauge lengths (1 mm, 2 mm and 4.5 mm) were chosen. Excitation and evaluation of

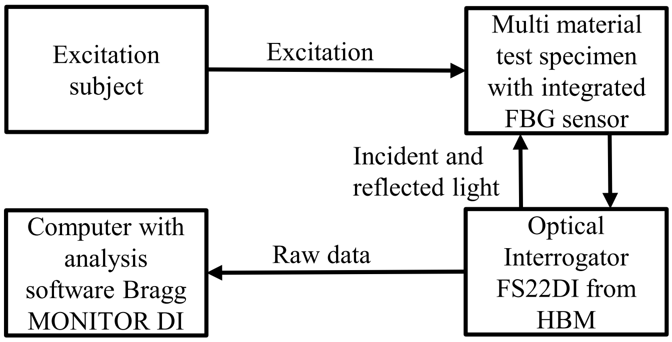

Figure 2: Schematic representation of the measurement setup

the FBG sensors were carried out by the optical interrogator FS22DI (HBM) with a maximum acquisition rate up to 1000 S/s. The analysis of the raw data was conducted with the analysis software BraggMONITR DI (HBM).

2.2. Simulation and manufacturing of test specimens

In order to investigate the detection of natural frequencies and thus the detection of component defects by means of FBG sensors, test specimens with a metal substrate and an outer skin made of glass fiber reinforced polymer composite (GFRP) were designed. For consideration of the effects of two different kinds of clamping (fixed/loose and loose/loose) appropriate fixtures have been provided. With fixed/loose clamping, one side of the specimen is fixed while the other side can vibrate freely. In a loose/loose clamping the whole specimen can vibrate freely without restrictions.

To guarantee that the measurement of the test specimens is possible with the available hardware, a simulation with the finite element method (FEM) was carried out. For complex geometric structures of multi-material components with different material properties, such as Young´s modulus and density, FEM simulation allows the investigation of their vibration properties with little effort. According to the Nyquist-Shannon sampling theorem, a maximum natural frequency of 500 Hz can be measured at a sampling rate of 1000 Hz of the available interrogator [17]. The measurement resolution of the interrogator is 1 Hz. In order to detect measurement effects, which occur as a percentage of the natural frequency, as precise as possible, high natural frequencies are advantageous. The FEM simulation therefore aims to achieve the highest possible natural frequencies below the measurement limit of 500 Hz for both kinds of clamping.

Therefore, the geometry of the test specimen was adapted and simulated in iterative steps (Figure 3, a)). The simulation was performed using the Workbench modal analysis simulation in ANSYS 2021 R1. For the metal substrate of the steel alloy 316L, the material properties according to the manufacturer´s specifications were used. For the outer skin, the values for GFRP from the ANSYS materials database were applied. Solver type and determination of element size were automatically determined by the program. The simulation results for the final geometry are depicted in Figure 3, b). Values of 84 Hz (fixed/loose) and 427 Hz (loose/loose) were detected.

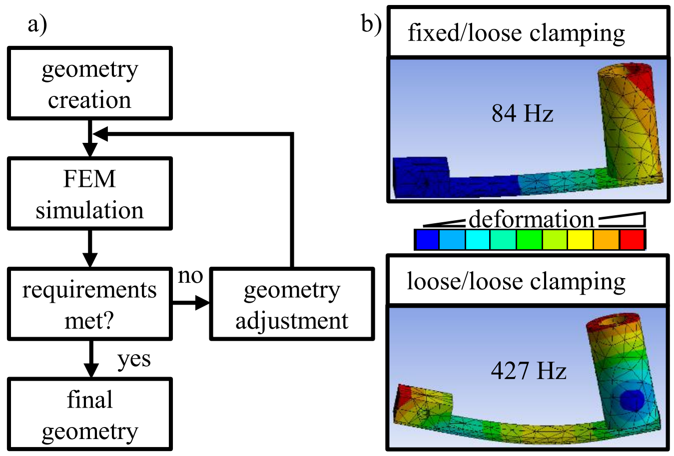

Figure 3: a) Iterative determination of the test specimen geometry, b) Mode 1 of the natural frequency of the final test specimen (deformations of the component are exaggerated)

The final version of the simulated test specimen (see Figure 4) was manufactured in two steps. The metal component was produced by Powder Bed Fusion of Metals using a Laser Beam (PBF-LB/M) on an SLM125HL machine from SLM Solutions. After the build process, the test specimens were separated from the build platform by wire electrical discharge machining. The outer GFRP skin was then applied to the flat side of the specimens, where they were cut off the build platform. The curing was carried out in a vacuum assisted resin infusion (VARI) process. Two layers of a biaxial glass fiber scrim (-45°, +45°) supplied by Hexcel Cooperation and the resin system AH 140 / TC 90-2 supplied by Ebalta were used. The FBG sensors were placed between the metal and the GFRP counterparts.

Due to deviations in the manufacturing process, namely when separating the metal body from the build platform and when hand-laminating the outer skin, the material thicknesses slightly differ from the ones used in simulation. Thickness of the metal body and the FRP layers showed lower values (0.1 mm for the metal body and 0.9 mm for the FRP layers) compared to the simulation ones, which consequently affects the natural frequency of the test specimens.

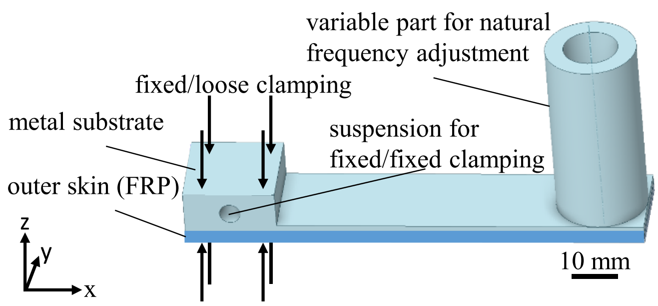

Figure 4: Schematic illustration of the final test specimen geometry

3. Results

3.1. Natural frequency verification on test specimens

In order to prove that the measurement setup can be used to determine natural frequencies on the test specimens, one test specimen without defect was measured several times successively in both clamping modes (fixed/loose, loose/loose). For the fixed/loose clamping the specimen was fixed only on one side in a vice. The excitation was conducted on the other side by a rubber mallet. Since a loose/loose clamping is only possible in theory it was approximated by a one-sided suspension of the specimen with a rubber band. After excitation with the rubber mallet at the same spot as with the other clamping, the specimen was able to almost vibrate freely. For each clamping mode five measurements were performed, mean values result in 52.8 Hz (coefficient of variation (CV) of 0.0076) and 355 Hz (CV of 0.0018) for the fixed/loose and loose/loose mode respectively. As the results for the loose/loose clamping have a much smaller CV, the following measurements on the test specimens were carried out with the loose/loose clamping.

3.2. Excitation parameters and FBG influences

After the successful detection of natural frequencies, the best possible settings for the detection of defects in the components had to be defined.

Therefore, the influences of varying the main excitation parameters, namely frequency, direction and location of the excitation, were examined (see Figure 5). All parameters were tested 5 times, each under two different conditions. For all parameter variations the 95 % confidence interval (CI) was calculated (error bars in the figure). The excitation frequency varied between 1 Hz and 3 Hz with resulting mean values of the natural frequency of 355 Hz (CI of ± 0.55) and 355.2 Hz (CI of ± 0.66). The excitation direction was tested in z- and x-direction of the specimen with resulting natural frequencies of 355 Hz (CI of ± 0.55) and 355 Hz (CI of ± 0.67). The excitation location was changed between location 1 and location 2, the two ends of the test specimen. Mean values of 355 Hz (CI of ± 0.55) and 355 Hz (CI of ± 0.18) resulted. Further, a combined CI for the related values was marked with grey areas in Figure 5, showing the overlapping parts of the single CI. As long as there is an overlap between the CI it could be assumed, that the variations did not lead to a significant change of the measuring results. This was the case for the three examined parameters.

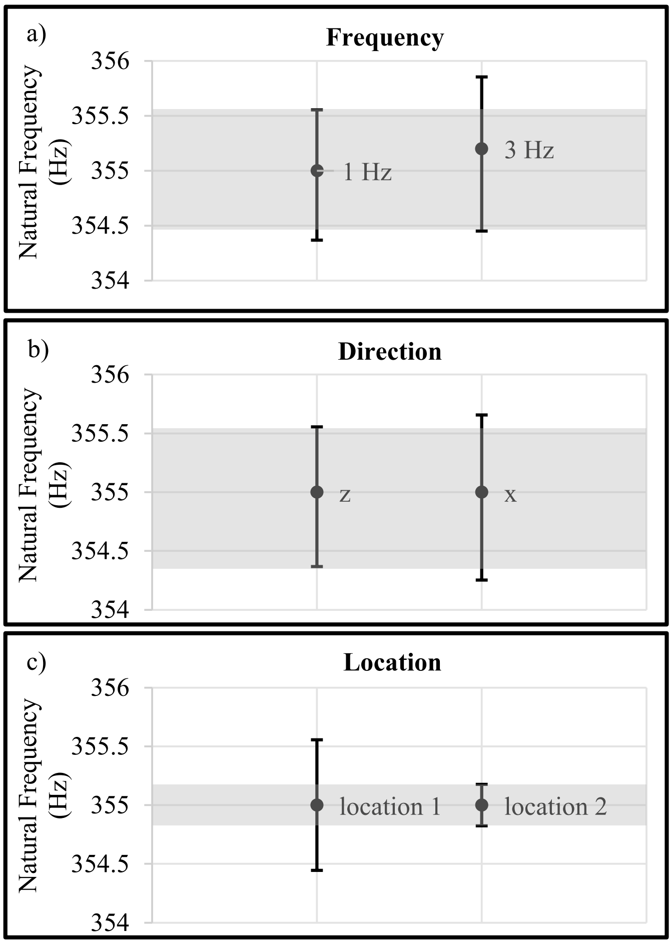

Figure 5: Influence of the excitation parameters frequency, direction and location on the measurement of natural frequencies

In addition to the excitation parameters influences through the FBG sensors were examined. It was shown, that neither the orientation nor the location of the measuring points in the test specimens had any influence on the natural frequency. Moreover, the gauge length also had no effect on the conducted measurements.

The conducted experiments evidence a high robustness of the measuring setup against variations in the excitation and FBG influences. Only in the measurable amplitude of the natural frequency some differences could be observed. The amplitude reached its maximum when the excitation and the orientation of the measuring point was along the direction of motion of the natural frequency.

3.3. Detection of component defects

It was demonstrated that natural frequencies could be reliably detected independent from several influencing factors. In a next step the detection of component defects by the measurement setup was addressed. As there were fluctuations in the manufacturing process of the test specimens, that affected the natural frequency, two measurements were necessary. One to determine the individual natural frequency of the intact specimen and a second one after the induced damage to check, if significant differences in the natural frequency are detectable. To cause damage in the form of delamination in the specimen, an impact damage was induced with a drop tower and an appropriate weight. In order to determine at what level of damage detection was possible, the impact energy was gradually increased from 10 J to 40 J in steps of 10 J. After each step the natural frequency was determined, before the next higher impact was applied to the already damaged spot. With increase in impact the damaged area of the specimen expanded.

Figure 6 shows the evaluation of the test. The specimen without defect (301.4 Hz) and its 95 % CI (± 0.43) is marked in grey. For the impact of 10 J (301.6 Hz ± 0.43) and 20 J (301 Hz ± 0.44) the 95 % CI still overlapped with the one of the undamaged specimen. Consequently, no significant change in the natural frequency could be detected. An impact of 30 J (298.8 Hz ± 0.35) caused a defect in the specimen that led to a significantly lower natural frequency. The corresponding minimal defect size for detection with the measurement system

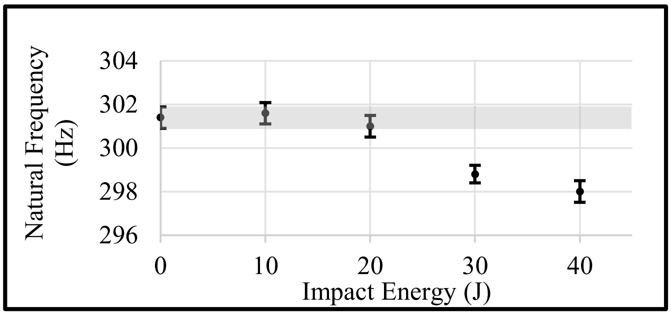

Figure 6: Change of the natural frequency due to defects caused by increasing impact energies

is 63 mm². At an impact energy of 40 J (295.6 Hz ± 0.43), the observed trend was continued and the natural frequency decreased further.

3.4. Transfer to demonstrator application

The functionality of the measurement technique was further tested on a demonstrator from the sport sector. As an example a snowboard was chosen as the demonstrator, which was considered to be suitable since it is a multi-material component that meets lightweight criteria and has to withstand high and irregular loads.

The snowboard was constructed as a sandwich component with a wooden core and GFRP skin layers with embedded FBG sensors. Again, the sensitive outer skin performs sensory tasks to monitor the core structure, as in the bone as a bionic role model. To fix the bindings metal inserts, manufactured in the PBF-LB/M process, were used. For defect detection two FBG sensors with six measuring points each were integrated in the upper GFRP skin layer.

Due to better feasibility the fixed/loose clamping mode was chosen for the measurement. Just as with the measurement of the test specimens a reference measurement was performed to determine the natural frequencies of the snowboard in a state without defects. The drop tower was used again to initiate a single impact of 50 J to cause a damage. The corresponding defect size was recorded at 144 mm². The snowboard with the embedded FBG sensors and the impact defect is depicted in Figure 7.

While for the test specimens only one natural frequency was measurable, for the demonstrator with and without the defect six natural frequencies were within the measurable frequency spectrum. These different natural frequencies are called modes. In mode 1 (undamaged: 19 Hz, CI of ±0.18; damaged: 19 Hz, CI of ± 0.18) and 5 (undamaged: 294.6 Hz, CI of ± 0.66; damaged: 295 Hz, CI of ± 1.41) no trend of a change between the two states was detected. Mode 2 (undamaged: 41 Hz, CI of ± 2.39; damaged: 39 Hz, CI of ± 1.41) and 3 (undamaged: 294.6 Hz, CI of ± 0.66; damaged: 295 Hz, CI of ± 0.18) showed a reduced frequency. However, the change was within the CI of the undamaged snowboard and did not allow for a clear statement. For mode 4 (undamaged: 199.2 Hz, CI of ± 0.35; damaged: 202 Hz, CI of ± 0.18) and 6 (undamaged: 401.2 Hz, CI of ± 0.66; damaged: 408.6 Hz, CI of ± 1.19) a significant increase in natural frequency was detected. It was assumed that these modes have a different mode shape than the ones detected in the test specimens, which is based on torsion instead of bending of the component. Figure 8 shows an example of the evaluation for modes 3 and 4.

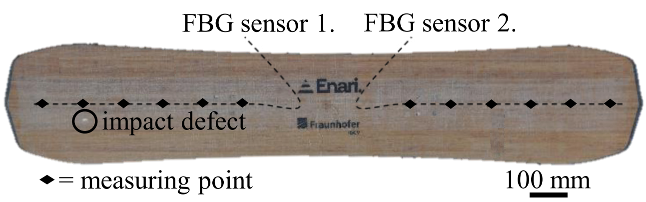

Figure 7: Snowboard as demonstrator application with two embedded FBG sensors, impact defect and six measurable natural frequencies (modes)

The tests on the demonstrator component confirmed the measurement results on the test specimens and showed that the measuring system was able to detect defects in multi-material components. The minimal detected defect size for the test specimens was 63 mm², for the demonstrator 144 mm². This makes it an interesting approach for further applications where SHM in multi-material components plays a role.

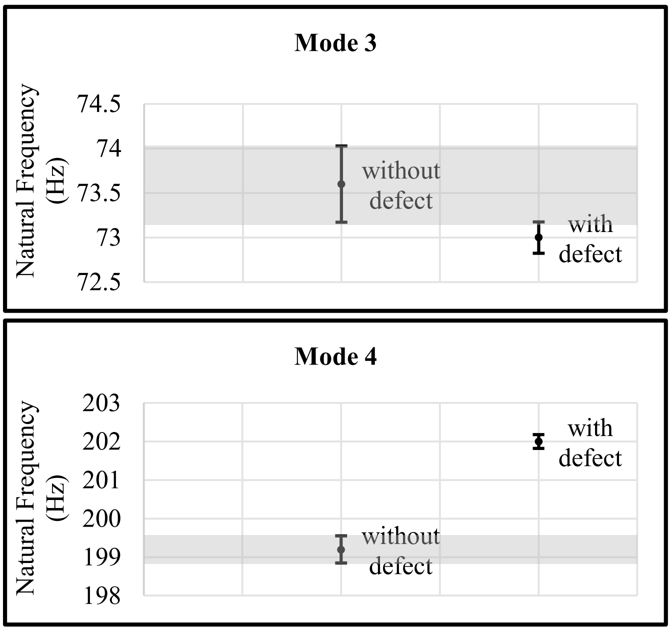

Figure 8: Evaluation of modes 3 and 4 to compare the natural frequencies of the demonstrator with and without defect

4. Discussion and Outlook

The described bio-inspired set-up using FBG sensors for SHM applications represents a promising approach especially for defect detection in multi-material components exposed to high and irregular loads. The approach was demonstrated with FBG sensors placed in between the GFRP layers of a hybrid component and the detection of defects via analysis of the natural frequencies.

Although the system was very robust against changes in the excitation, the amplitudes of the natural frequencies varied. An interrogator with a higher acquisition rate as the one that was used for the described tests would allow the analysis of a wider range of frequencies and realization of more precise measurements.

Furthermore a larger data set and more detailed analysis of the effects of defects on the amplitude and different modes of the natural frequencies could allow for a localization and size determination of the defects.

Due to fluctuations in the manual production of the test specimens and the demonstrator, measurements in two states, with and without defect, had to be conducted to make a statement. In series production with less fluctuations in production quality it could be interesting to test the measurement system for quality control. The assumption would be that all good parts have the same natural frequency, while defected parts deviate from that.

The presented approach further addresses other industries than sports, as chosen for demonstration purposes. The implementation of FBG for SHM allows components to be replaced or serviced only when necessary, furthermore lightweight construction potentials can be fully exploited. With further development of the system other sectors such as the automotive, robotic and aerospace industries could benefit by reduced maintenance costs and increased safety.

Author Contributions

Moritz Warnck: Conceptualization, Methodology, Visualization, Writing – Original Draft. **Maximilian Binder:** Project administration, Conceptualization, Writing – Review & Editing. **Georg Edelmann:** Methodology, Investigation. **Marion Früchtl:** Funding acquisition, Writing – Original Draft, Review & Editing. **Iman Taha:** Conceptualization, Writing – Review & Editing

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