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Validation of an inside sensor system for deformation measurements on bionic lightweight gears

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Summary:
To validate design guidelines of bionic, holistic lightweight gears with integrated load monitoring, an inside sensor system will be used to continuously record the deformation behavior under dynamic load. Strain gauges based on thin-film technology and metal substrate are used as sensors for this purpose. Measurements on a gear show that, during the entire tooth meshing, the deformation behavior of each tooth can continuously be measured with the implemented inside sensor system and that the various tooth meshing zones can also be detected.

Keywords: bionic lightweight gear, inside sensor system, deformation measurements, dynamic load

Introduction

Due to steadily increasing dimensions of wind turbines (WT), the trend of an increasing resource consumption for gears in WT gearboxes is emerging. To conserve resources, design guidelines for bionic, holistic lightweight gears with an integrated load monitoring are designed and validated. For the real-time load monitoring in the future and for the validation of the design guidelines, an inside sensor system is required. The inside sensor system directly characterizes the deformation behavior of the lightweight gears in operation, which is unknown, especially in the case of dynamic loads and, thus, enables load monitoring to predict material failure.

Due to the unknown deformation behavior, the bionic, holistic lightweight gears cannot be validated and observed with conventional condition monitoring systems [1, 2] when used in wind turbine gearboxes, because they do not record the deformations and loads directly at the gears. Conventional methods for recording forces and deformations are based on strain gauges, but so far, they lack robustness against adverse environmental conditions for long-term measurements [3]. Also, tactile and optical gear measuring systems [4, 5] are generally suitable for direct deformation measurement on gears, but not during dynamic loads. Indeed, the current studies have not yet addressed the detectability of deformations on bionic, holistic lightweight gears and of load peaks for real-time load monitoring.

Therefore, the aim of this work is to validate an inside sensor system for measuring the tooth deformation of lightweight gears under dynamic load conditions. The research question to be answered is whether the implemented inside sensor system can be used to continuously measure the deformation behavior of all teeth, i. e. the entire tooth mesh of all teeth.

Methodology and experimental setup

An inside sensor system is used to measure the mechanical stress states and the resulting deformations of dynamically loaded gears. Due to handling and compatibility with the test environment, the inside sensor system is first characterized on medium straight-toothed classical gears with involute profile. The gears have a pitch diameter of 120 mm, a module of 8 mm and 15 teeth each. The contact ratio of the gear teeth is approx. 1.3, so that alternating one pair of teeth is in single mesh and two pairs of teeth are in double mesh. The gears are made of case-hardened steel 16MnCr5.

The sensors used in the inside sensor system are 4.5 mm x 9.5 mm strain gauges from Siegert TFT, based on thin-film technology and metal substrate. Four sensor elements are each designed as meander-shaped measuring grids and arranged at 90° angles to each other. The interconnection is based on the principle of a Wheatstone's measuring bridge in the configuration of a full bridge. The strain gauges are welded directly to the gear. To identify the appropriate sensor position and orientation, FEM simulations localized the maximum stress concentration and stress directions on a loaded tooth in the area of the tooth root. To validate the measurability of the entire tooth mesh, three strain gauges are each welded to adjacent teeth. According to the contact ratio of the gears, the measurement signals of the successive strain gauges are expected to have temporal overlaps.

The measured strain is initially output in µV/V and can be converted to mm in the future. In order to record the measurement signals of the strain gauge bridge in real time, a telemetry system from imc Test & Measurement, rotating on the shaft, is used for data transmission.

For the validation of the sensor system, the gears are integrated in a shaft test rig and dynamically loaded. The experimental setup is illustrated in Fig. 1.

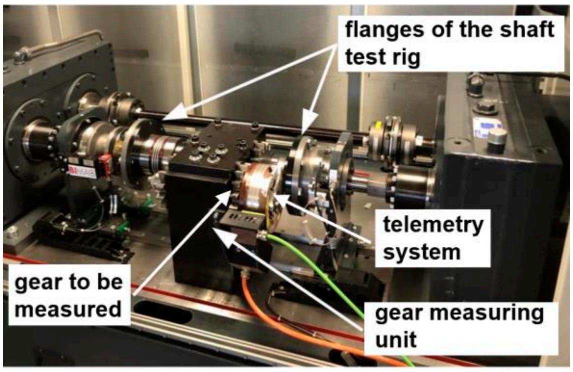

Fig. 1: Experimental setup for dynamically testing the inside sensor system to detect the entire tooth mesh.

Results

The focus of the observation is the measurability of the entire tooth mesh in order to characterize the deformation behavior of loaded teeth of lightweight gears and real-time load monitoring in future. According to a first gearbox stage of a wind turbine, a speed of $n = 15\ \text{min}^{-1}$ is initially set within the scope of the validation of the inside sensor system. The load is set to 100 Nm.

The results of the measurements demonstrate a signal overlap of the successive strain gauges, which is consistent with the expectation (cf. Fig. 2). In addition, the experimentally determined average gear meshing time for 15 min^{-1} is 0.287 s, which agrees well with a theoretically calculated gear meshing time of 0.284 s. As a result, the measurements validate that the total tooth meshing can be measured with the implemented inside sensor system.

Furthermore, the different meshing zones, single meshing and double meshing can also be distinguished in the signal curve of the strain gauges. At the start of meshing (A), the measurement signal initially increases abruptly. At this point, the signal curve overlaps with the measurement signal of the previous tooth, which decreases abruptly. It is hypothesized that the gear teeth are in double meshing in this state. When the double meshing is finished (B), the tooth meshing changes into a single meshing (B-D) and the slope of the signal curve changes abruptly. As soon as the next pair of teeth begins to mesh with each other, the gear is again in a double meshing (D-E).

In summary, the experiments validate the inside sensor system for measuring the deformation behavior of gears under dynamic load. With the selected sensor position and alignment, the entire mesh of a tooth can be measured with only one sensor.

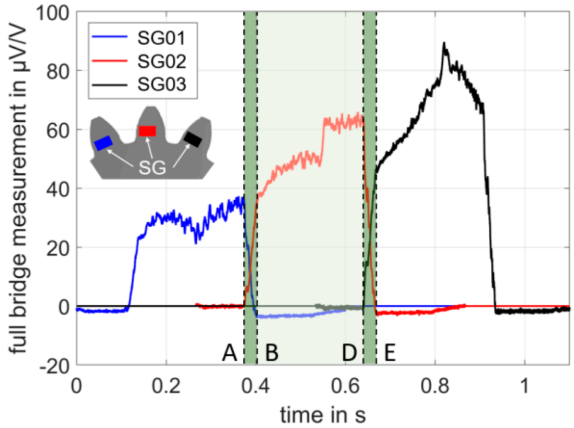

Fig. 2: Strains measured with the strain gauges (SG) of the inside sensor system during tooth meshing. A to E indicate different tooth meshing conditions. Note that the amplitudes of the strain gauges vary due to deviations in the alignment of the gears, but this does not affect the evaluation of the inside sensor system in terms of the measurability of the entire tooth mesh.

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