Response to Referee Comments #1, wes-2021-69

RC2: 'Comment on wes-2021-69', Hongkun Zhang, 02 Nov 2021
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Thank you for your positive feedback and constructive comments, which we consider helpful in improving the quality of our paper. All comments have been addressed below and the manuscript will be revised accordingly.

This manuscript presented a high-quality research with a new approach for measurement of the gearbox input torque. Different from the traditional way using strain gauge on the rotating shaft, optical FBG strain sensors were used here on the stationary gearbox housing. Additionally, the alternating part of the signal (due to gear meshing) was used for the torque measurement instead of the absolute value of the signal. As a result, the method can overcome some of the major difficulties in the traditional ways of torque measurement and can be seen as a promising method - at least for certain applications like condition monitoring. However, the method still has to be quantitively validated and certain concerns (from my point of view) still need to be clarified in the **future**:

- The influence of the non-torque load
- Strain distribution along the length of the tooth
- The stability of the calibration under different load cases and over time
- The speed of data processing and possibility of real-time high-frequency measurement
- Time expense in the instrumentation of FBG sensors and cost of interrogator (share use with other measurements?)

The authors have managed to apply the method on a real-size wind turbine gearbox in a professional test campaign and properly analysed the measured data with novel processing methods. Generally, the manuscript presented a high-quality research and made scientific contributions in the measurement and processing methods while proposed a promising method for the industrial application at the same time.

We fully agree with the suggested future work and are actively seeking ways to accomplish these research topics:

- Quantitative assessment of the accuracy of the proposed method.
- Test this new method in an environment with non-torque loads, either in a suitable test bench or directly on a wind turbine.
- Study the effect of load distribution along the face width of the gears on the outer surface strain measurements.

- Repeatability of results over time.
- Cost improvements for serial implementation.

Regarding the content of the manuscript, I would like to give my comments in **the following points**:

1. Section2.3. The position and direction of the FBG sensors.

After reading the manuscript I would assume that the FBG sensors are installed in the mid-line of the ring gear outer surface and that the sensors are measuring strain in the tangential direction. But since this method was new to me, it took me some time to wonder where exactly and what kind of strains are measured. It would be helpful to add the information explicitly in the text or under one of the figures.

Your assumptions are correct. The fibers were placed in the middle sections of the ring gear in the axial direction. The fibers run tangentially to this section, covering the complete revolution along the outer perimeter of the ring gear. The FBGs measure the deformation of the outer surface of the ring gear in the tangential direction of Figure 2.

We acknowledge your comment and will clarify this point in the revised manuscript.

2. Section 2.3 and Section 2.5. Temperature.

I think more clarification is needed regarding to temperature influences. As is known that FBG sensors are prone to influences of temperature changes, it is expected from a reader with measurement background that the signal with measured temperature somehow compensated. In the manuscript, it is only mentioned that two temperature sensors are available. After reading through, several questions arise:

- A) are two temperature sensors enough?
- B) at which positions are the two temperature sensors located?
- C) it looks that the temperature measurements are not used in the post processing, the signal was simply detrended instead. why?

With the given information I could only imagine: the methods focus only on the changes in the strain signals and therefore are not sensitive to the long-term drift caused by temperature change? A temperature non-uniform distribution along the circumference causes probably only a 1P contribution to the Coleman method and very small influence on the 5P, which is used for the torque measurement? Can you please give more words on the topic of temperature influence?

Again, your assumptions are correct, and we agree that more clarification on this topic will be beneficial. We will modify the manuscript to add further explanations on how we dealt with temperature effects.

The wavelength reflected by the FBGs shift both due to temperature changes in the grating and due to strain (Section 2.3.). The FBGs we used in our study have a theoretical sensitivity to strain of 1.19 pm wavelength shift per μm/m strain and 27.9 pm/$°C$.

Coming back to your specific questions:

A) In the fiber setup explained in Section 2.3. we describe the arrangement of the FBGs. Each fiber was manufactured with 14 gratings to give a total of 56gratings. We decided to use 54 of these gratings for strain measurements in the points described in Figure 2.
With the two remaining gratings we attempted a temperature measurement to gain information about the temperature in the ring gear and the potential difference in temperature of different locations. A small tube was placed around the fiber to prevent the effect of strain on the reflected wavelength. However, the installation was not completely successful, and we could not use the data.

B) These two gratings were placed in the vicinity of the strain sensors S02 and S29. Our reasoning for choosing these locations was that the lower part of the ring gear immersed in the oil bath could have a different temperature to the top.

C) We did indeed detrend the signal to remove the long-term drift caused by temperature, and we assigned the remaining alternating signal as purely caused by the strain imposed from the meshing of the planets. As explained in Section 2.5. we did not perform real-time analysis of the strain signals and the data was detrended prior to processing.

Your suggestion about the potential effect of a non-uniform temperature distribution on a real-time scenario is very interesting and we will try to address it in future work. All the tests presented in this study were performed under stabilized temperature conditions. The effects of transient operating conditions with large temperature gradients need to be studied.

3. Section3.2. Difference in linearity.

For discussion: could it be that the position of the FBG sensor relative to the nearby tooth/teeth has some contribution to the difference in the slops? The sensor directly under a tooth will likely experience different strain progress as the sensor laying under the middle of two adjacent teeth. Otherwise, the distribution of strain along the length of the tooth could theoretically also play a part.

We agree that the position of the strain sensors relative to the gear teeth, which does change for the different angular positions, and the load distribution along the face width may influence the slope of the strain to torque relationship. However, we failed to understand why some sensors have a more linear behavior than others.

4. Page 20, line 333. Correlation of the phase angle with the torque.

It appears to me that the phase angle describes how the strain are distributed along the circumference upon a certain point of time and is mostly dependent on the azimuth angle of the planet carrier. Is there theoretical basis supporting the correlation?

Our theoretical assumption to expect a change in the phase angle is based on the torsional deformation of the planet carrier caused by the torque. The azimuth of the shaft was given by the once-per-revolution pulse from the inductive sensor placed on the rotor side flange of the planet carrier. The phase angle depends on the azimuth angle, but we were expecting to observe a phase delay related to the amount of twist in the carrier, which would increase with the torque.

5. Figure 22 and 23. Comparison with HSS torque possible?

I'm wondering why the HSS torque was not included in the comparison figures. A direct thought will be to compare the measurement with the calibration reference, which is the mean value of the HSS torque times gearbox ratio. Despite of the dynamics inside the gearboxes, such a comparison can still show the low-frequency behaviours of the measurement. Is there a reason that the HSS torque are not drawn in the figures for comparison?

For the calibration phase, we used the signals precisely as you describe. We multiplied the torque measured by each transducer at the high-speed shaft by the gearbox ratio and then computed the mean value of the two gearboxes. This does not capture the dynamics of the gearboxes and we felt we could not use this computed signal to compare the high-frequency input torque estimates. Adding this reference torque value created graphs that were less clear and more difficult to read, so we decided to compare the two estimates without the reference. However, we did not consider filtering the high-frequency content to show the low-frequency behavior. We will consider this suggestion for the revised manuscript.

The followings are comments for the text and language, only as recommendations.

6. Line 61. "3-stage" gearbox.

Corrected in the revised manuscript.

7. Line 102&136. "on" the surface.

Corrected in the revised manuscript.

8. Line 114. "input load excitation"

Added in the revised manuscript.

9. Line 115. with the main axis "horizontal"

Rephased in the revised manuscript.

10. Line 140. the interrogator "sends" a full...

Changed in the revised manuscript.

11. Line 141. the word synchronize strongly implies the time sync. A better word should be possible here. For example, "associate"?

Changed in the revised manuscript.

12. Line 158. First, a "test" with a ...

Rephased in the revised manuscript.

13. Line 159. The sentence "In both variable ..." should be place in front of sentence "First, a test with ..."

Rephased in the revised manuscript.

14. Line 240. "As can be seen in ..."

Rephased in the revised manuscript.

15. Line 414. "On one hand, ..."

Rephased in the revised manuscript.

Thank you!