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Real-time Monitoring of Wind Turbine Generator Shaft Alignment using Laser Measurement

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Abstract

Shaft Misalignment is one of the most common sources of trouble of wind turbine drive train when rigid couplings connect the shafts. Ideal alignment of the shaft is difficult to be obtained and the couplings attached to the shaft may present angular or parallel misalignment defined also as lateral and axially misalignment. Despite misalignment is often observed in the practice, there are relatively few studies on wind turbine shaft misalignment in the literature and their results are sometimes conflicting. The aim of this research is to use laser based metrology techniques to capture the positional changes of wind turbines in service and aligning drivelines in wind turbine. By using sets of lasers on a shaft alignment rig, and then determining the average and periodic amplitude from an ensemble averaged signal, the degree of misalignment can be found and the necessary corrective action found.

1. Introduction

The wind energy industry, that is the designing and manufacture of wind turbines with the resultant installation and day-to-day operations, is growing fast and is set to expand as the UK and the rest of the world look for leaner and more sustainable ways to generate electricity. Turbines are becoming of greater value in terms of whole life-cycle operating cost versus power generation, with larger blade lengths and greater area and number of turbines in a wind farm, resulting in an increase in margin from electricity generation. Optimisation of the power delivery from the wind turbines is therefore of great interest to maximise the return on investment made.

Wind turbines are unmanned, remote power plants which, unlike conventional power stations, are highly exposed to dynamic and harsh weather conditions, with wide ranges of heat, wind speeds, and all the meteorological wear that could be expected from unprotected hill tops or the marine environment, resulting in wind turbines experiencing a constantly changing load pattern. As a result of these highly variable operational conditions there are high mechanical stresses on wind turbines unmatched in any other form of power generation, which require a high degree of maintenance to provide a safe, cost effective and reliable power output for an acceptable equipment life cycle, such as detailed by Andraus [1].

The wind industry currently uses only Reactive Maintenance (fix it when it breaks) and Preventive Maintenance (following the wind turbine manufacturer's service manual) and has not fully developed techniques in the newer forms of maintenance collectively known as Predictive Maintenance (Pruftechnik [2]) which uses technical condition monitoring technologies. There are several condition monitoring techniques available, including vibration analysis, thermography, strain measurement and self-diagnostic sensors [3]. The objective of this research is focussed on using laser based metrology techniques to capture the positional changes

of wind turbines in service and aligning drivelines in wind turbines. In this way the mechanical operation, and therefore the aerodynamic design and loading predictions, of the turbine can be more accurately predicted and thus lead to the improved efficiencies.

2. Motor Shaft Alignment

The method of offering a technical solution to monitoring the mechanical operation of wind turbine will focus on the alignment of the critical components, which are the wind turbine's blade and generator. In a large-scale wind turbine there is a coupling connecting the generator to the blade hub that connects the propeller shaft to the generator's drive shaft. These couplings need to be kept in perfect alignment otherwise losses and damage may occur, detailed by Jesse [4], such as:

- Extreme radial and axial vibrations
- Oil leakage at shaft seals and bearing seals
- Hot couplings or High casing temperatures at or near bearings
- Loosened coupling bolts or foundation bolts
- Premature bearing or shaft wear and failure

Though small degrees of misalignment do not cause transmission losses, it is still a serious concern. Lin et al detected the motor shaft alignment using mutiscale entropy with wavelet denoising [5]. Lees investigated the misalignment in rigidly coupled rotors [6], Pennacchi et al modelled the nonlinear effects caused by coupling misalignment in rotors [7]. However these tests tend to be one-off tests and are not conducted based upon shaft misalignment and additionally there is no regular monitoring. In order to perform regulator monitor, measurements need to be taken as in Figure 1, from Vesta [8], below:
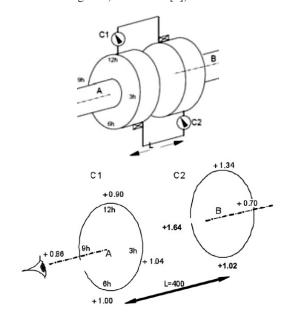

Fig. 1. Shaft alignment procedure

The 'C1' and 'C2' locations are measurements located at an angular difference of 180°. The longer the distance of 'L' is the better, as it increases the sensitivity of angular error detection. The readings should be performed at least 4 times for the 'C1' and 'C2' measurement locations: that being at the 12h, 3h, 6h, 9h clock-wise locations. The results from these measurements can then be evaluated as in Figure 2. The values given are an example in millimetres, where the reading is considered positive (+) when the measurement is towards the shaft. In assessing the measurements referring to the vertical plane, the deflections are shown below as an example:

Considering the vertical plane of 'C1', the vertical action towards the top of shaft 'A' on the measurement device is dominant. In the plane 'C1' the axis 'A' is higher than axis 'B' (at 0.05mm average deflection at 180° opposed measurements). In the vertical plane measurement 'C2', as shown in Figure 2, shows that the vertical action towards the top of shaft 'B' measured is greater. In the plane 'C2' the axis 'B' is higher than axis 'A' at 0.16mm. Therefore in the vertical plane the angular alignment error can be evaluated as 0.0525 mm.
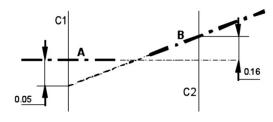

Fig. 2. Eccentricity calculation geometry – vertical axis

Measurements can therefore also be taken referring to the horizontal axis, as shown in Figure 3 below:

In this plane, 'C1', the axis 'B' is further to downwards than 'A' at 0.09mm of deflection. In the plane 'C2' the axis 'B' is further upwards than 'A' at 0.47mm of deflection (again, average deflection at 180° opposed measurements). As such the horizontal angular error can be evaluated as 0.14mm.
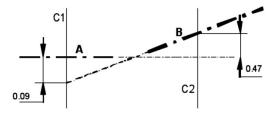

Fig. 3. Eccentricity calculation geometry – horizontal axis

3. Real-time Alignment Measuring – Laboratory Study

In order to perform real-time shaft alignment, a laboratory test rig has been created that operates at the typical rotational rates of a wind turbine in the order of 120rpm using two lasers. The general assembly, as shown in Figure 4 is a motor that simulates the turbine rotating, connected via a straight shaft to two flanged couplings and a flexible coupling. Two measurement devices evaluate the distance to pulleys

mounted on both sides of the motor shaft flanged and also flexible coupling (to separate tests). These lasers determine the variation in radii of the shaft as it rotates. A photosensitive sensor is used as a rotary encoder to determine when the shaft has completed a rotation, and via an electronic comparator, gives a TTL trigger signal. Additionally the alignment calculation, as shown in Figure 2 and Figure 3, to determine horizontal and vertical alignment can be computed 'on the fly' and hence the measurement of misalignment can be readily evaluated. The test was conducted on both the flanged coupling used to test radial misalignment and the flexible coupling used to test axial angular misalignment.
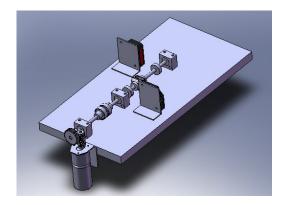

Fig. 4. Shaft alignment test rig CAD model

In this test, the physical structural deformation of the shaft is not experimented as the lasers would equally measure alignment error whether it was caused by poorly connected couplings or shaft deformation, either way each result would show a delta movement in shaft distance.

4. Experimental Results

Preliminary tests showed nominal variation in alignment deviation with rotational frequency or torque, and therefore tests were run at a fixed nominal speed of 120rpm only. Laser measurement distance and trigger were logged at around 16 periods of shaft rotation. Four serial tests have been performed:

- Lasers targeted at flanged couplings, couplings laterally aligned
- Lasers targeted at flanged couplings, couplings laterally misaligned
- Lasers targeted at flexible couplings, couplings axially aligned
- Lasers targeted at flexible couplings, couplings axially misaligned

4.1. Flanged couplings lateral aligned

Results for this test configuration can be seen in Figure 5 showing the results for multiple shaft rotations, and then Figure 6, showing the results ensemble-averaged for the periods shown in Figure 5. The results are interpreted by looking at differences in the average between the two sides of

the coupling (which shows shaft misalignment) and then variation in amplitude as the shaft rotates (which represents eccentricity of the coupling alignment). So, ideally, the shafts will have the same average and little amplitude variation during rotation. It can be seen that when the flanges are correctly aligned, the variation in distance of the coupling wall varies only nominally though a minor variation of a few decimals of a millimetre can be seen. Equally the downstream coupling, representing the fan shaft, also has a nominal coupling wall distance variation. The results of the time history were then time averaged, in Figure 6, which shows very good correlation between the two laser distance measurements. Note the peak seen, especially in the fan shaft trace, which presents the cut-away in the flanged coupling, evident in the images of the flanged coupling presented earlier. No correction is made in any of the results presented for the 180° phase shift between the motors, as the proposed method uses periodic peak-to-peak measurements and as such no alignment of instantaneous measurement result is required.
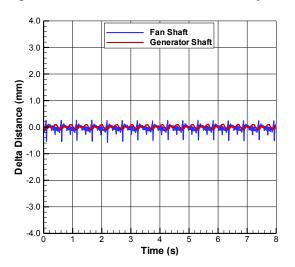

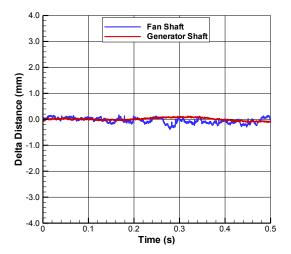Fig. 5. Flanged coupling, laterally aligned, time history data

Fig. 6. Flanged coupling, laterally aligned, ensemble averaged data

4.2. Flanged couplings lateral misaligned

The tests were now repeated with the flanged coupling misaligned, with the time history and ensemble averaged data shown in Figure 7 and Figure 8 respectively. It can now clearly be seen that there is both a DC shift between the fan and generator shaft reading and also periodic amplitude due to the misalignment. The ensemble averaged results also show the clear variation in coupling sidewall distance with rotation, with a clean signal seen for the generator shaft and a more noisy (mainly due to the rapid variation in distance relative to laser response time) trace evident for the fan shaft.
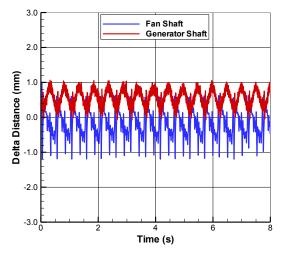
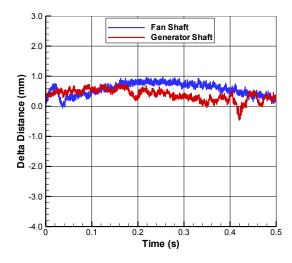Fig. 7. Flanged coupling, laterally misaligned, time history data

Fig. 8. Flanged coupling, laterally aligned, ensemble averaged data

The peak-to-peak variation for the fan shaft was found to be $^+/-0.49$mm, with an average of $+0.51$mm, and the peak-to-peak variation for the generator shaft found to be $^+/-0.38$mm, with an average of $^+/-0.32$mm. With C_1 as 1.00 and 0.02mm and C_2 as 0.70 and -0.06mm, the vertical alignment of drive shafts for lateral misalignment is 0.085mm and horizontal alignment of drive shafts for lateral misalignment is -0.002 mm.

4.3. Flanged couplings axial aligned

The lasers were then remounted, with the distance measurement targeted on the flexible flange sidewalls, with the results reported in Figure 9 and Figure 10 for the time history and ensemble-averaged data, respectively. It can be seen that there is a nominal sidewall distance variation with shaft rotation on both the fan and generator shaft sides of the coupling, with the spike in the time history data representing the cut-away in the coupling for the fixing grub screw (visible in images of the flexible coupling earlier). The ensemble-averaged data, in Figure 10, also clearly shows neither no DC shift nor periodic variation in the sidewall distance.
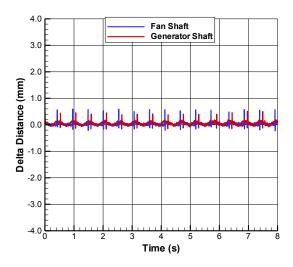
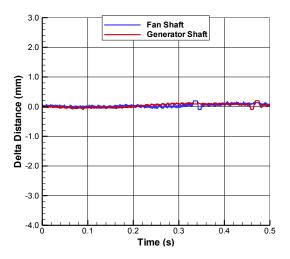Fig. 9. Flexible coupling, axially aligned, time history data

Fig.10. Flexible coupling, axially aligned, ensemble average data

4.4. Flanged couplings axial misaligned

Figure 11 and Figure 12, show the results for the time history and ensemble averaged data, respectively. It can be seen that, though step change exists between the sidewall measurements either side of the coupling, the couplings are clearly out of alignment due to the periodic amplitude. The ensemble-averaged results show much less noisy results relative to the time history, suggesting that the ensemble averaging offers a far clearer result. It can also be seen in the ensemble averaged result prominent peaks where the cut-away for the grub screw is located, and the distinct peak at this location confirms accurate shaft angle triggering (otherwise the peak would be smoothed). The results show that the generator shaft has an average result of -0.12mm and an amplitude of 0.24mm, versus an average of -0.08mm and an amplitude of 0.76mm for the fan shaft measurement. It is expected that the fan shaft deflects more greatly than the generator shaft due to the test rig applying the misalignment on the fan shaft side.
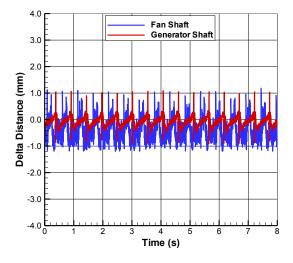
The peak-to-peak variation for the fan shaft was found to be $^+/-0.56$mm, with an average of -0.18mm, and the peak-to-peak variation for the generator shaft found to be $^+/-0.28$mm, with an average of -0.04mm. With C_1 as 0.38 and 0.74mm and C_2 as 0.24 and -0.32mm, the vertical alignment of drive shaft for axial misalignment is 0.031mm and the horizontal alignment of drive shafts for axial misalignment is 0.021mm.

5. Conclusions

This research has shown test rig and processing techniques are able to, in real-time, determine the degree of misalignment in drive shafts. Data has been collected using laser distance measuring devices with a high response rate (<10ms) and accuracy (<1mm) to measure shaft deflections on either side of couplings and blade deflection. By using sets of lasers on a shaft alignment rig, and then determining the average and periodic amplitude from an ensemble-averaged signal, the degree of misalignment can be found and the necessary corrective action taken.

Two types of coupling have been used in this research. Flanged couplings allow tests for lateral misalignment. Flexible coupling imposes a test for axial misalignment. From the results we can see that the use of a shaft-aligned trigger signal allowed the measured distances to undergo ensemble averaging. This technique lent itself strongly to the objective specification and proved a valid method for producing low noise measurement signals. The results clearly showed distance measurements could be processed to find a maximum and minimum deflection over the rotational period, which can then be used to determine the degree of misalignment and the direction to which the shaft should be realigned.

Fig.11. Flexible coupling, axially misaligned, time history data

Fig.12. Flexible coupling, axially misaligned, ensemble average data

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