Grease sampling and analysis for in-service Condition Monitoring (CM) of wind turbine blade bearings

Hans S. Møller[1], Kim H. Esbensen[2], Rich Wurzbach[3]

[1]COWI A/S, Visionsvej 53, DK 9000 Aalborg, Denmark
[2]Geological Survey of Denmark and Greenland (GEUS) & KHE Consulting
[3]MRG Labs, 410 King Mill Road, York, PA, USA

Abstract

Representative in-service sampling of grease from wind turbine blade bearings is a prerequisite for development of a routine Condition Monitoring based on grease analysis. Due to the current design, proper grease sampling (Theory of Sampling, TOS) is impossible as the grease is not directly accessible when the turbine is in operation. However the present study finds that used grease collectors (grease cups in this project) contains wear particles of the same morphology and size as the grease in the active zone of the bearing, strongly corroborated by detailed microscopy and analytical ferrography. This is a decisive finding, proving pervasive internal transport of grease along the full circumference of blade bearings. We conclude that grease cup sampling is fit-for-purpose representative for the entire bearing grease. The present study concerned deep groove ball bearings (DGBB); the present findings may likely also apply to other turbine sizes and types if equipped with similar type of blade bearings.

Keywords:

Wind turbine blade bearings, grease sampling; Theory of Sampling (TOS): grease analysis; condition monitoring (CM)

1 BACKGROUND - SCOPE

DONG Energy A/S and Statkraft AS wish to develop a reliable and cost effective method for condition monitoring of wind turbine blade bearings based on analyses of extracted grease samples. This necessitates a method for representative *in-operation* sampling of grease from bearings, which is not current considered feasible while the wind turbines are in action. The present project benefitted greatly from a regular maintenance program in which it was possible to carry out extraction of representative grease samples (in the sense of the Theory of Sampling, TOS) from blade bearings in Siemens 3.6 MW turbines. This served as a reference against which yearly grease cup sampling could be evaluated. A key part of the project was made possible due to intervention by Siemens Wind Power, Denmark (SWP), who supplied the two bearings used in the project and committed highly experienced staff and the equipment necessary for dismantling the two project bearings.

The basic principles for representative sampling derive from the Theory of Sampling (TOS), presented here with the minimum basic concepts and terms necessary for this paper only. Full introduction to TOS are found in the standard DS 3077 "Horizontal – Representative Sampling" (2013) [1], [2], [3].

"Lot" here denotes the total body of grease in a specific bearing, the properties of which are to be determined by extraction of one or several "increments". Properly extracted increments may either be analysed as individual samples and/or may be aggregated to form a "composite sample" (bulk sample). The former approach allows mapping of the full 3-D distribution of the relevant analytes within the bearing raceway, while the latter allows a representative average analyte concentration of the entire bearing lot to be estimated.

In this project, the lot is thus the total amount of grease present in one blade bearing of a 3.6MW turbine, with a 107m rotor; typically this is 8.5 kg varying according to operational conditions.

Representative sampling requires a. o. that all compositional constituents of the grease, including introduced wear metal fragments, are physically available for sampling with equal probability for representative extraction; this demand is called TOS' Fundamental Sampling Principle (FSP). This condition is not possible to fulfil when taking samples from turbines in operation, as the grease surrounding the bearing balls and on the raceways are not directly accessible under these conditions.

A central issue in this project has therefore been to establish whether the grease available for sampling with the alternative grease cup approach (GC) and/or sampling from outlet holes (OH), has the same composition and characteristics as the lot material in the bearing(s). This question can only be answered by dismantling a blade bearing in order to make all parts of the lot accessible, thereby establishing a reference sampling, with which to compare these two proxy approaches (GC, OH).

2 REFERENCE SAMPLING (3-D CHARACTERISATION)

Samples were extracted from two randomly chosen SWP 3.6 MW turbine, 107 m rotor blade bearings, as part of a yearly service schedule. The bearings have been in operation for about 8 years and are both of the deep groove ball bearing type (DGBB). In Fig. 1, a complete bearing can be seen with a number of "grease cups" fitted to the inner ring.

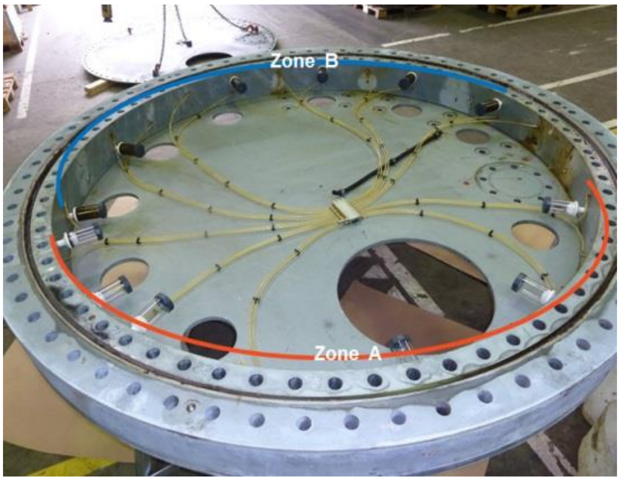

Figure*1*: SWP 3.6 MW turbine blade bearing with grease cups fitted to the inner ring. In “Zone A” (foreground) no grease were found in any cup, while cups in “Zone B” were all filled to capacity, due to a combination of gravity, centrifugal forces and blade orientation, see technical report [4] for full explanation. The present project uses samples from zone B only.

Each bearing has twelve 250 ml grease cups evenly distributed along the circumference of the inner ring, which are used to collect used grease from the bearing. Grease cups are changed once a year at normal service intervals. The capacity of grease that can be collected is 6 x 250 ml, or approximately 1,500 g of grease per year per bearing.

With the bearing dismantled, it is possible to conduct sampling in a representative fashion according to TOS. This approach allows complete characterisation of the variation and properties of the grease along the entire 360 degree active zone of the bearing in the space between the raceways. This sampling scheme is termed the 3-D heterogeneity characterisation and forms the reference sampling against which the alternative grease cup/outlet hole approaches shall be evaluated. As this characterisation is fit-for-purpose representative, it will be the best available estimate of the properties of the lot, be this as an average over the full circumference of the bearing ring or as a mapping of the peripheral compositional variation in the active zone between the raceways.

3 NORMAL IN-OPERATION SERVICE SAMPLING

During normal operation, at regular yearly service intervals, samples can only be taken by using grease cups (GC) or through sampling from the outlet holes (OH), see Fig. 2. Outlet holes are drilled holes in the inner ring through which excess grease flows into the grease cups.

Figure 2: Extraction of an increment (using a straw) from an outlet hole (OH) (left) and via grease cups (GC) (right), the latter producing temporal composite samples covering a year, approx. 250 ml.

A total of 179 samples were extracted from the two blade bearings [4].

4 ANALYTES

The contents of ferromagnetic iron, FdM-Fe and water was determined in all samples. The content of a number of other chemical elements (including iron) was also determined using the Rotating Disc Electrode method (RDE), the current standard method for measuring additives and wear metal in lubricating grease. It is a major objective of the present study to compare and evaluate these alternative analytical approaches. Selected samples were also subjected to a microscopy investigation of the type of wear particles, as well as subjected to analytical ferrography.

5 FUNDAMENTAL SAMPLING ISSUES

Iron content is likely the most important single parameter for evaluating the operational condition of any grease-lubricated component. For measuring iron and other elements in lubricating grease, the RDE method was used in this project. The quantity needed for an RDE test is very small (250-500 mg) however, which requires a careful sample mass reduction before analysis – a requirement that is often overlooked, see [5]. However, the RDE method cannot handle particles, e.g. wear particles, larger than *a few* µm. Special care was taken in this project to perform this mass-reduction according to the principles of the Theory of Sampling (TOS), *ibid* and [1] avoiding otherwise typical sampling errors in the laboratory.

The sampling issues cannot be overemphasised. Non-representative primary sampling give rise to the absolute largest sampling error potential ‘from-field-to-analysis’, typically at least 10 X the following laboratory sampling errors - especially if the primary sampling procedure, knowingly or unwittingly, is deliberately aimed at direvtly procuring a sample only as large as to the analytical mass. This type of sampling, mimimum mass grab sampling, will always give rise to a maximum impact of the Fundamental Sampling Error (FSE) [1], making grease cup/outlet hole sampling vs. 3-D reference mapping, as well as iron determination comparions much less feasible, see also [4]. All of these traditional sampling errors have been suppressed in the present study, in order to secure an optimal basis upon which to carry out the specific project objectives.

The present samplingprocedures were developed over time; earlier results were presented in the previous LUBMAT conferences [6], [7].

6 COMPARISON RDE vs FdM-Fe

FdM-Fe (ANALEX fdM plus Ferrous Debris Monitor) is a magnetometer designed to measure ferrous wear particles in grease and oil. It is different from the RDE method in two ways: the whole grease sample is analysed, obviating the need for mass-reduction, and all ferrous wear particles are measured irrespective of particle size. The FSE has been suppressed maximally with this approach.

Fig. 3. shows FdM-Fe plotted against Fe as measured with the RDE method in the 3-D reference mapping of the full complement of 61 circumferential primary samples (we here show results from bearing 002 but results for bearing 001 are similar).

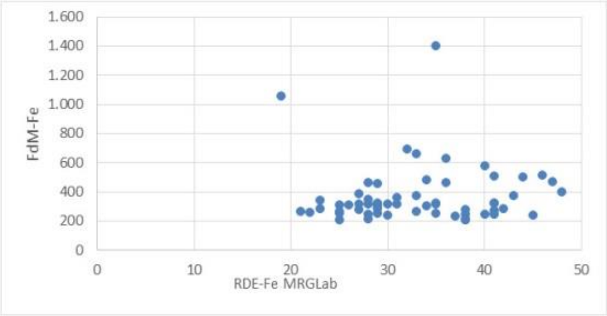

Figure 3: Correlation plot between FdM-Fe and Fe RDE in 61 3-D reference samples (bearing 002)

Fig 3 clearly demonstrate that there is no correlation between the two alternative methods, but instead show very large differences in the measured absolute levels of Fe. All the RDM Fe results are below 50ppm, while the FdM Fe results vary from some hundred ppm to 1,400 ppm(sic). Some samples contain particles many of which are larger than 10-20 µm. As the RDE method only detects particles smaller than some few µm, in these cases it will unavoidably give rise to highly misleadingly low Fe content values. On this basis, it can be concluded that FdM-Fe is the only reliable method that can be used for estimating the content of ferrous magnetic wear particles in grease from blade bearings.

All the samples extracted with grease thieves in this project were analysed by two labs in parallel, the NJV-lab and MRGLab respectively; results are presented in Fig. 4. As Fdm-Fe is a non-destructive method, it was possible to have both labs analyse the same samples *in toto*.

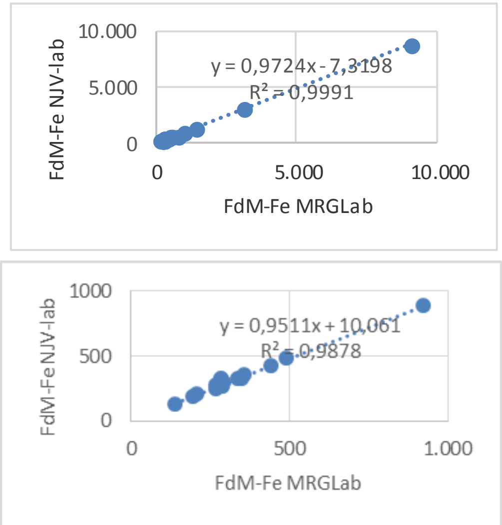

Figure 4: Correlation between FdM-Fe results from NJV-lab and MRGLab in 61 reference samples from bearing 001 (left) and rom bearing 002 (right).

Fig. 4 demonstrates a very strong linear relationship between the results of both two labs. This documents an excellent inter-laboratory reproducibility of the FdM-Fe method.

7 MICROSCOPY

Microscopy and analytical ferrography of series of selected samples show presence of a number of large wear particles, both in the reference samples and in the grease cup and outlet hole samples. These particles originate in a so-called "soft spot" zone on the bearing raceway. At the time of the manufacture of the bearings, the induction method used for hardening the bearing races required leaving a small area untreated in order to avoid treating it twice. The untreated area of the race way was ground back to reduce contact pressue; Fig. 5 shows how wear now takes place at both transition areas between the hardened and the unhardened area.

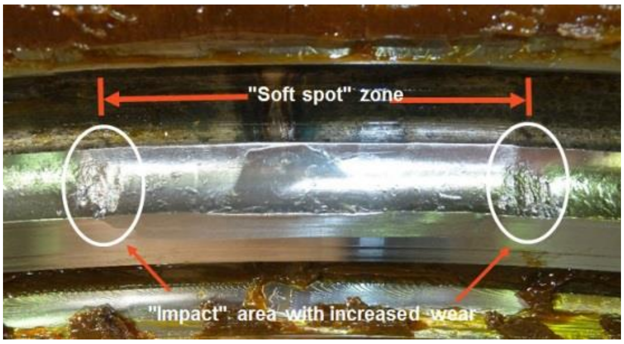

Figure 5: Soft spot location on the inner race showing the two areas with severely increased wear.

Detailed peripheral 3-D sample mapping and characterisation has shown that these large wear particles, which are only created at the edges of this soft spot zone, are present everywhere in the bearing grease. This can only be explained by a substantial transport with the grease inside the bearing. This observation was unknown prior to this experiment.

As samples taken for this reference characterisation can be considered fit-for-purpose representative in the project context, because all of TOS' fundamental principles are respected, the present results can therefore be considered as un-biased estimators of the 'true' grease properties of the lot (bearing raceway).

8 GREASE CUP vs. REFERENCE ANALYTICAL RESULTS

By comparing the analytical FdM-Fe results of the sample set taken from grease cups and outlet holes with the reference 3-D samples, it is possible to evaluate the degree of similar compositional features with the former. In Fig. 6 results for FdM-Fe in bearing 001 are shown - together with results for water content shown in Fig. 7.

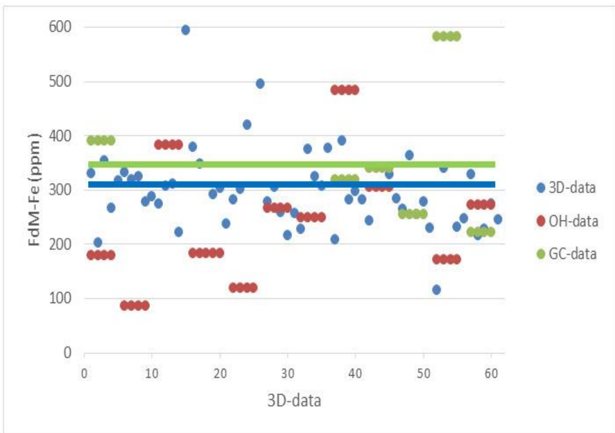

Figure 6: Comparison of 3-D FdM-Fe data from grease cups (GC) and outlet holes (OH) compared with the reference data (3-D) for blade bearing 001. The blue line shows the average value for 3D samples, the green one for grease cup samples.

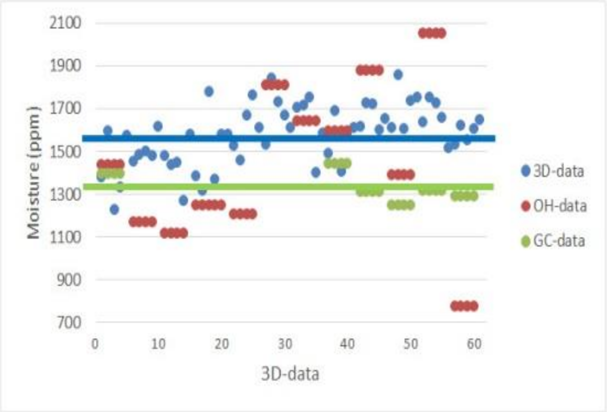

Figure 7: Comparison of 3D moisture data from grease cups (GC) and outlet holes (OH) compared the reference data (3D); blade bearing 001. The blue line shows the average value for 3D samples, the green one for grease cup samples.

While there can be observed an appreciable localised analytical result variability, the overall bearing behaviour (averages of 3-D, GC and OH data respectively) is striking. Figures 6 and 7 demonstrate a quite satisfactory agreement between the average values from the 3-D data (reference values) and samples from the grease cups. This indicates that routine samples from one (or more) grease cups (preferentially) can be used to estimate the FdM-Fe and water content of grease in the "active" bearing parts, i.e. the contact zone between balls and raceways. The outlet hole data (OH) are much more variable in comparison. It would not appear possible to base routine inspection on OH samples.

9 WEAR PARTICLE CHARACTERISATION

Size and morphology of wear particles are central to estimating the wear condition of a bearing. Sampling from grease cups and outlet holes will only yield useful results if they contain particles of the same type, size and morphology as the reference 3-D samples. A detailed morphological examination was carried out, full documentation to be found in [4]. This study found an extensive similarity between wear particles from the grease cups and outlet holes and particles in the 3-D reference samples.

These results, as well as those obtained by extensive analytical ferrography (technical report) [4] show that grease cups and outlet hole samples contain the exact same types and sizes of particles as found in the 3-D samples.

It can be concluded that grease sampled by way of grease cups for all practical purposes has the same FdM-Fe, water and wear particle characteristics as that of the 3-D samples.

10 CONCLUSIONS

Representative in-service sampling of grease from blade bearings is a prerequisite for development of a routine Condition Monitoring. Due to the design of current blade bearings, direct representative grease sampling (in the sense of Theory of Sampling, TOS) is impossible as the grease is not directly accessible when the turbine is in operation. However, the results of the present study leads to the conclusion that sampling of grease from 'grease cups' is for all practical purposes a satisfactory *proxy* for representative sampling.

The project was predicated on the fact that the selected test bearings from SWP 3.6 MW wind turbines had a defect, a so-called "soft spot". These have generated diagnostic, clearly recognisable wear particles, some of which are very large (>200 µm). Although generated at only one focused location in the bearing they are now found in the full circumference of the raceway grease and in the grease collected in the grease cups. This is a decisive finding as it proves a pervasive internal transport of grease along the full circumference of blade bearings. The present project has shown that all grease cups containing grease contains wear particles of the same morphology and size as the grease in the active zone of the bearing. This conclusion is corroborated strongly by detailed analytical ferrography, see technical report [1].

The objective of the project was to study the feasibility of a method for representative sampling of grease from blade bearings in SWP 3.6 MW turbines. The objective has been achieved as it has been shown that grease sampled with grease cups is representative of that in the complete bearing. Grease cup sampling can be accomplished as part of a standard regular service regimen. The same conclusion does not hold for grease samples obtained via the outlet holes (OH).

The blade bearings were all deep groove ball bearings (DGBB). The present results, which focused on SWP 3.6MW wind turbines only, may likely also be applicable to other turbine sizes and types if they are equipped with similar type of blade bearings turbines.

REFERENCES

[1] DS 3077 (2013) Esbensen, K.H.(chairman taskforce F-205 2010-2013). DS 3077. Representative sampling - Horizontal Standardǁ. Danish Standards. www.ds.dk

[2] Esbensen, K.H, Wagner, C. (2014) *Theory of Sampling (TOS) versus Measurement Uncertainty (MU) – a call for integration*. Trends in Analytical Chemistry (TrAC), vol 57, pp. 93-106

[3] Esbensen, K.H. & Mortensen, P. (2010). *Process Sampling (Theory of Sampling, TOS) – the Missing Link in Process Analytical Technology (PAT)*. in Bakeev, K. A. (Ed.) Process Analytical Technology. 2.nd Edition. pp. 37-80. Wiley. ISBN 978-0-470-72207-7

[4] Møller, H., Esbensen, K.H., Wurzbach, R. (2015) Analysis of blade bearing greases: Final project report and executive summary. November 2015

[5] Petersen, L, C. Dahl, K.H. Esbensen (2004). Representative mass reduction in sampling – a critical survey of techniques and hardware. in Special Issue: 50 years of Pierre Gy's Theory of Sampling. Proceedings: First World Conference on Sampling and Blending (WCSB1). Esbensen & Minkkinen (Eds). *Chemometrics and Intelligent Laboratory Systems*, vol. 74, Issue 1, p. 95-114

[6] Møller, H., Giselsson, T.M., Wurzbach, R., Esbensen, K.H (2012) Analysis of Grease in Wind Turbine bearings – a tool for condition monitoring, *LUBMAT2012, Bilbao*

[7] Møller, H., Wurzbach, R., Esbensen, K.H., Larsen, U., Giselsson, T.M., Ukonsaari, J. (2014) Analysis of Grease in Wind Turbine bearings – a tool for condition monitoring. Part 2, *LUBMAT2014, Manchester*