

Grease Sampling and Analysis for Wind Turbines and other Bearing and Gear Applications

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Summary

Oil analysis is well established as a routine tool to optimize maintenance activities, improve reliability and equipment life and prevent component failures. As part of a comprehensive Condition Based Maintenance program, lubricant analysis is an effective complement to other diagnostic technologies such as vibration analysis, infrared thermography, ultrasonic detection and motor circuit evaluation. However, when the equipment is grease lubricated rather than oil lubricated, the important lubricant analysis piece is often left out of the mix. The reasons for this include challenges in obtaining samples that can be trended, as well as the large sample volumes required for most current standardized tests for greases. Unlike oil, grease does not typically flow uniformly or circulate in the machine, so particulate and contaminants are present in varying concentrations in the grease. When a grease sample is obtained, it cannot be simply agitated to suspend and distribute particulate, as is the case with oil. These fundamental differences present barriers to acceptance of grease analysis as a routine aspect of diagnostic monitoring programs. New tools have been developed for improved sampling techniques and grease analysis tests have been added to address concerns of sample trending as well as accommodating small sample sizes. These include rheometry of greases, for which DIN standards exist and ASTM standards are under development. Other new tests are emerging, including die extrusion, to efficiently prepare samples for analysis. Novel sampling aids are being introduced to permit consistent extraction of samples from locations that improve the representative nature of the sample.

This paper will discuss how these new technologies can produce improvements in reliability and reductions in lubrication costs through condition-based greasing and trending of wear levels, with samples as small as 1 gram. Advantages of preparing substrates with a thin-film grease deposition are discussed for purposes of more streamlined and uniform sample preparation for subsequent analysis. A colorimetric method for evaluating characteristics of new greases, and chemometric methods for evaluating contaminant levels for in-service greases are also discussed. Wind turbines, motors, motor operated valve gearboxes, and robotic assembly examples will be given for these cost-benefits, and case studies will be shared that demonstrate the return on investment in routine grease sampling and used grease analysis technology.



Figure 1: Grease sampler installed in a motor test stand

1. Obtaining Samples

In most circumstances, procedures for obtaining grease samples from bearing housing and gears are not consistent and likely do not represent the true condition of the “active” grease near the lubricated surface. It may also contain particulate and other contamination picked up during the sampling process. Historically, in-service grease samples from motors, valves, and various bearing housings, typically have required the equipment to be out of service and disassembled. A key factor is that a large volume of sample is needed to perform current analytical testing methodologies and along with this issue is that it is extremely difficult to obtain that representative sample from near the bearing while the component is still in service.

Therefore the challenge in optimising a grease analysis program is the development of test methodologies to measure in-service grease conditions utilizing a smaller amount of grease and a sampling process that enables representative grease samples be taken without disassembling of the component. For motors and certain other components with grease drain paths, new design components are available that allow a replaceable fitting to be installed at the drain port (Figure 1). This fitting serves two purposes. First, it takes the place of a drain plug, allowing displaced grease to drain from the cavity without building up pressure--compromising the bearing shield/seal. Secondly, it provides a protected pathway for representative grease which drains from the cavity to be captured and submitted for analysis.



Figure 2: Grease sampler for motor drains

In this new design, the sampling fitting is also optimised for the subsequent laboratory analysis. By providing a sealing surface in the fitting cylinder, the entire volume of grease is available for analysis. Extraction of the grease is done under variable pressure and force conditions, and the response of the grease can be measured and related to the grease consistency and flow characteristics, important

considerations for in-service greases. As the grease is extruded for analysis, it can be delivered in a thin film for accurate analysis by FTIR, RULER, spectral analysis, and other tests, giving detailed information about grease oxidation, contamination, mixing and wear.

For motor operated valves, gearboxes, and bearings that do not by design deliver grease to a drain point, other sampling tools have been developed. Similar to the principle of a liquid sample “thief”, the device must be able to travel from the access hole to the active lubrication location, near the bearing or gear mating area, and bypass the non-representative grease along the way. This requires the device to push grease out of the way in the space between the access hole and the lubricated surface, and then capture a small amount of grease close to the gear surface or bearing grease shear area. Such a device has been developed and tested to demonstrate the capability to deliver a representative sample.

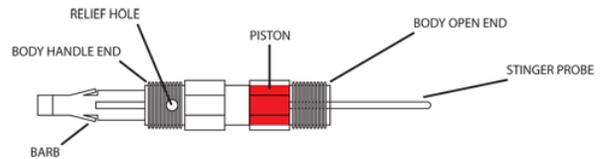


Figure 3: Grease sampler for gearbox testing

The grease sampler is inserted into a t-handle extension to permit remote actuation and capture of the sample at the site of active grease use and wear generation, adjacent to the mating gears or bearing surface.

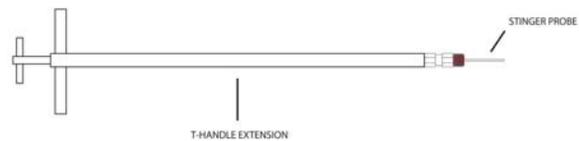


Figure 4: Grease sampler in t-handle extension

2. Grease Wear Testing

2.1. Test stand



Figure 5: Motor Operated Valve (gearbox) test stand

To begin the required analysis for this experiment samples were collected from a Limitorque Actuator in a test stand. Two such valves are utilized in the test stand, MOV-104 and MOV-121. MOV-104 is an SMB-0, and MOV-121 is an SMB-00. The grease samples were obtained by application of a Grease Thief Type II grease sampler with stinger probe and a retractable T-handle tool. The Grease Thief was positioned so that the stinger probe was completely exposed. The Grease Thief and T-handle was placed into an open hole, made available by removing a threaded plug. This port was located on the top of the MOV, directly above the worm or mating pinion gears. After the sample was collected the Grease Thief was cleaned off and capped. After each sample, the MOV was run to the full closed position and then to the full open position, each cycle consisting of an approximately 45 second run of the motor at normal synchronous speed. This allowed for additional grease to return to the section of the MOV that was sampled. For some testing, twenty open and close cycles were performed between samples, but this proved to have little impact on the wear concentration, possibly owing to the lack of gross faults in the tested components.

2.2. Wear Analysis Methods Comparison

To begin the grease analysis the iron concentration was determined by using the FdM+. Each sample was run three times, and the data from them was averaged to obtain a representative measurement. The repeatability of the FdM+ method was extremely good, with moderate variation on the three runs for a given sample (blue trend

line in Figure 6). The first five samples were disregarded, to allow for thorough mixing and stabilization of the wear levels. The remaining eight samples were evaluated for comparative analysis against traditional oil analysis debris monitoring techniques.

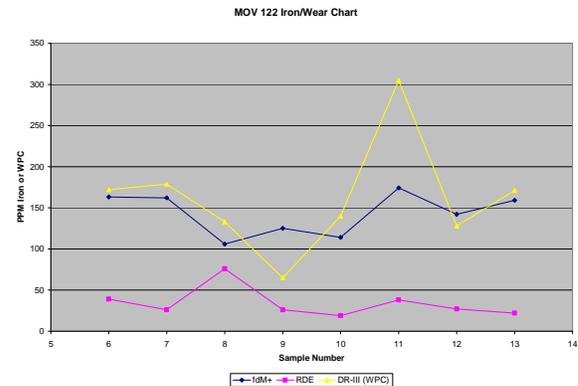


Figure 6: Steady-state wear level comparisons

As the FdM+ values could be directly measured in the sampling device, further treatment was needed to obtain the additional wear results. To prepare the samples for further analysis they were processed by the Grease Thief Analyzer. This instrument extrudes the samples onto a low density polyethylene substrate while determining their consistency. A 0.25 gram sample was weighed out into a 20 mL scintillation vial. A 5 mL portion of a 50:50 mixture of heptane and toluene, grease solvent, was dispensed into the vial. Approximately 5 to 10 glass beads were added to the vial to help break up and dissolve the grease. The vial was then agitated with an orbital shaker for 5 minutes to obtain satisfactory dissolution of the grease. A 10:1 dilution was prepared with filtered blank oil for the DR-III test. To make this dilution, 1 mL of the original sample was mixed with 9 mL of filtered blank oil in a scintillation vial and agitated for 5 minutes on the orbital shaker. Once the sample preparation was complete, this procedure was repeated for the next portion from this sample. Where sample quantity permitted, three such preparations were made for comparison.

Text.

2.3. Wear Comparison Results

This first graph shows a comparison of ferrous debris measurement techniques from consecutive samples taken from a Limitorque Actuator, a gearbox used in Motor Operated Valves.

The graph (Figure 6) shows the variability seen in the RDE (spectroscopy) and WPC (ferrography) values, which are derived from a weighed portion of the obtained sample. Meanwhile, the FdM+ results are obtained by presenting the entire sample in the Grease Thief™ in the FdM+ unit. The ability to present the entire sample for analysis without compromising the ability to perform further tests for contamination, oxidation and consistency, provides a more consistent trend of the wear condition. Statistical analysis of these results are shown in the following table:

Sample #	fdM+	RDE	DR-III (WPC)	Plot Data #
420	163	39	172	6
421	162	26	179	7
422	106	76	133	8
423	125	26	65	9
424	114	19	140	10
425	174	38	305	11
427	142	27	128	12
428	159	22	171	13
Average	143.1	34.1	161.6	
StdDev	25.4	18.3	68.5	
RelStdDev	17.7	53.7	42.4	

Figure 7: Statistical Analysis of grease wear monitoring technologies

The relative standard deviation value for the FdM+ shows much greater consistency in the samples. To further evaluate the reasons for this, and to test for variability in ferrous debris concentration through a given sample, a selected number of samples in a separate experiment, again from a Limitorque gearbox, were extruded to prepare several analyses for each 1 gram sample from a grease thief. The relative standard deviation was then calculated for the RDE and WPC values to demonstrate the variability seen in a single sample when analyzed in three separate sections.

The results indicate a difficulty in obtaining trendable values for ferrous grease wear when employing methods that require dissolution of a portion of the grease sample and analysis of the liquefied sample in typical oil analysis instrumentation. This is due to the non-uniformity of distribution of wear in a grease sample, and the difficulty in achieving a uniform dispersion of that wear. Particle size limitations of those methods are similarly a concern. However, when utilizing a method that counts the entire ferrous content of the sample, this variation is minimized, and a more valid trend can be developed for samples from a given location. In any case, the challenges of obtaining samples that represent the condition of the

monitored component remain, and must be addressed satisfactorily to obtain actionable data on the wear condition of those components.

2.4. Wear Trending Test

In 2009, an EPRI project was initiated on greases that included testing the validity of the sampling method. This involved the construction of a test stand using SMB-0 and SMB-00 actuators from Progress Energy. Testing included fiber-optic inspections of operating actuators to observe the movement of grease that had been in service for several years in a power plant environment. This testing demonstrated the movement and mixing of grease that still maintained a consistency close to its original value.



Figure 8: Hall-effect (FdM+) sensor and Grease Thief

Other testing was performed to confirm the ability to develop consistent trends in wear levels, utilizing the Grease Thief geometry, and a Hall-effect sensor (Figure 8) to determine total ferrous wear content, in parts per million (ppm), for a given grease sample. In order to determine the ability to show trend changes in wear levels for known increased wear conditions, the SMB-00 actuator was deliberately misaligned. One hundred cycles of 90 seconds each were performed to first gather a stable baseline for total ferrous wear. Then shims were installed on one side of the motor mounting to induce a pinion gear misalignment and generate increased wear levels. 200 additional samples were taken in this misaligned condition, which showed a clear and significant increase in the wear trend (Figure 9) to confirm the increase generation of wear, and the ability of the Grease Thief sampler and Hall-effect sensor to obtain representative data for this excessive wear condition. These studies were published by the EPRI NMAC center in the Effective Grease Practices guide.

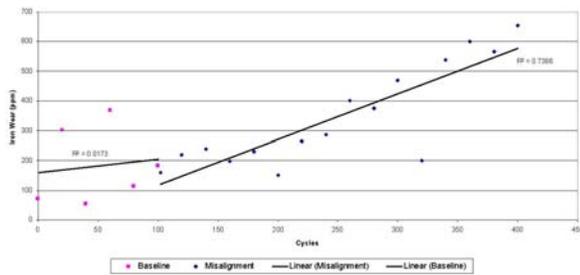


Figure 9: Increase in wear rate on pinion misalignment

3. Basic Analysis Options for Grease

The following tests make up a streamlined grease analysis process that takes advantage of the previously described sampling fitting. This allows the first two tests to be performed as part of the preparation of the sample for the subsequent tests listed. This reduces that amount of sampling handling and preparation required, and thus the potential costs of performing a meaningful and routine grease analysis for critical equipment.

3.1. Ferrous Debris Monitoring

A difficulty in evaluating wear particulate in grease exists because of the inability to agitate a sample to evenly distribute particulate, as is done with oils. This non-uniformity of distribution can lead to misleading results because the portion of the sample selected for dissolution and analysis may be skewed higher or lower with respect to wear particle content. One way to compensate for that condition is the use of a Hall-effect sensor to measure the entire ferrous content of the obtained sample. When using the sampling fitting described in Section 5, the entire volume of grease can be measured in a ferrous debris monitoring device that includes a chamber surrounded by the sensing coil. This method minimizes data scatter due to particle distribution issues and improves trendability and sensitivity of results.

3.2. Grease Consistency

By measuring the load under varying conditions during the extraction of the grease through the extrusion die, the consistency of the grease can be compared to the new grease consistency. Changes in this value, whether indicating a thinning or thickening of the grease, can be used to flag this property. Followup detailed analysis with a rheometer can further classify the condition of the

grease and relate to such parameters as dropping point and cone penetrometer, based on earlier studies by Nolan and Sivik [1] and Johnson [2]

3.3. Comparative FTIR Spectroscopy

FTIR spectra are created from new grease samples for all greases in a facility's program. Using a horizontal attenuated transverse reflectance (HATR) rig, a thin film of grease is applied across the crystal, and the auto-gain function is used to maximize signal and get a representative spectrum. Then the sampled in-service greases are tested and compared to the spectra of new grease. In particular, for different families of greases, the FTIR spectra are quite different and can be compared to see if significant mixing has occurred. In other cases, similar greases (two different polyurea greases) might not have significant differences in their spectra, but there is less likelihood of compatibility issues in that case. Still, many greases within the same family from different manufacturers can be differentiated with FTIR analysis. Also this test is valuable in monitoring for grease oxidation and the presence of certain organic additives. The Grease Thief substrate also holds value as a disposable IR sample cell, where the automatic preparation with the die extrusion process will speed the preparation and cleanup process, and further reduce costs associated with analysis.

3.4. Anti-Oxidants

The RULER instrument works on the principle of linear sweep voltammetry. By applying this test method, in which a variable voltage is applied to the sample while measuring the current flow, the presence and concentration of various antioxidant additives (including, but not limited to ZDDP) can be determined based on their unique electrochemical oxidation potential and the magnitude of the induced current. Monitoring residual anti-oxidants in purge greases can provide feedback on the effectiveness of grease relubrication frequencies. For example, a grease sample that has been purged from a bearing on the established relubrication interval, when analysed and determined to have a large amount (perhaps 70% or more) of residual anti-oxidants, and also shows good consistency characteristics, may be a candidate for extension of relubrication interval. Conversely, a purge grease sample that shows no or minimal (less than 25%) residual anti-oxidants may not be

completely protected from oxidative stressors during the grease life-cycle, and may appropriately be adjusted to a shorter relubrication interval.

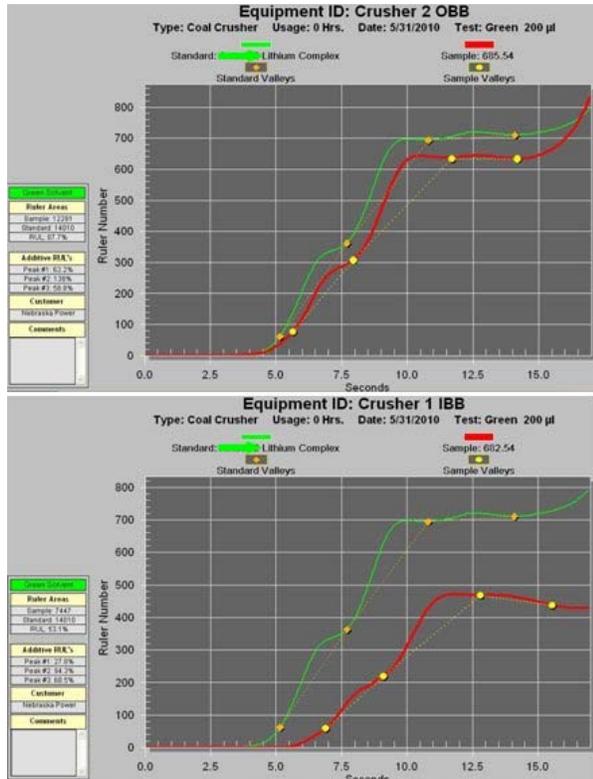


Figure 10: Colorimetric comparison of two greases, and a suspected mixture

3.5. Metals Spectroscopy

The grease is weighed out and added to a glass vial where it is diluted and dissolved with a filtered mixture of grease solvent. This liquid mixture is then analyzed by RDE (Rotating Disc Electrode) or ICP (Inductively Coupled Plasma) spectroscopy, and the results are ppm normalized to 1 gram of grease based on the measured weight of grease that was dissolved. The concentration of metals in the grease can be compared to the new grease for the purpose of identifying significant differences in additive metals that could point toward grease mixing. Also, the presence of wear metals can be deduced.

3.6. Grease Colorimetry

Visual observations of grease appearance are a common assessment tool for field evaluation of lubricated components. Appearance changes including darkening and unexpected or mixed colours are often the first



Figure 11: Spectrometer and optical cell for grease colorimetry

condition noted that may indicate unusual lubrication conditions or mixing. A desire to empirically evaluate and substantiate such observations led to the development of an optical cell, used to present a grease sample in a uniform manner for subsequent visible light spectral analysis (Figure 11). This grease colorimetry optical cell is designed to create an optical path for the i-Lab visible light spectrometer, and

includes a sliding drawer that presents the extruded grease thin-film on substrate produced from the Grease Thief die extrusion method. The resulting 0.040" (1.0 mm) pathlength is backed by a polished stainless steel mirror, which allows testing of the grease in a uniform

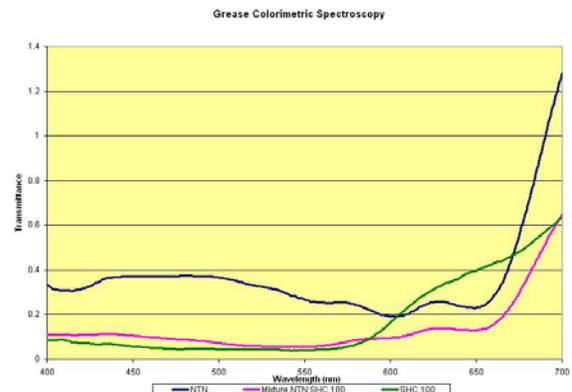


Figure 12: Colorimetric comparison of two greases, and a suspected mixture

manner without interference from ambient light and without contacting the grease sample.

The analytical result is a vector representation of the colour, in chromaticity and brightness. Also, a full spectral response of the grease in the 400-700 nm range is represented (as seen in Figure 12). This allows a qualitative comparison of grease colorimetric spectra to include as a data point to evaluate the likelihood of a used sample having constituent contributions from among some likely new greases.

The use of grease colorimetry as a chemometric method for determination of the quantity of a known particulate contaminant was evaluated. Figure 13 shows a series of spectra derived from the addition of a known quantity of coal dust. In an environment where grease is exposed to this contaminant, especially greases that are in storage or otherwise not substantially affected by other colour modifying influences, the method may be useful in quantifying these contaminants and comparing against guidelines for contaminant content limits.

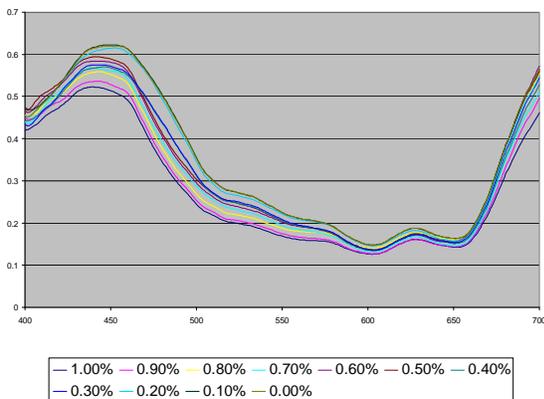


Figure 13: Spectral graphs of a grease with increasing quantity of dispersed coal dust

It has been suggested that grease colorimetry may have value in the manufacture of greases. Current commercial greases typically are dyed, for differentiation and marketing purposes. The specific colour of a grease becomes closely identified with the brand, and maintaining consistency in the colour of the product, while not affecting performance, may be important from a perception standpoint. Batch testing of greases by comparing an in-process batch with a colorimetric profile

may enable grease manufacturers to quantitatively evaluate colour and include a quality control step on appearance as part of the process.

4. Data Integration and Advanced Analysis

Together, these tests can be used to evaluate the condition of the grease, determine the extent of mixing with an incorrect grease, detect oxidation, measure the depletion of anti-oxidant additives, and categorize the extent of wear present in the sample. These tests can be done cost effectively because the consistency measuring instrument prepares the grease as a thin-film substrate for weight normalization and easy dissolution of the grease thickener, so the liquid sample can be analyzed with typical oil analysis equipment.

4.1. Additional Testing

If concerns arise during the above trending and screening process, follow-up analysis can be performed using the following tests:

Analytical Ferrography

This test can also be performed on the dissolved grease (prepared as for metals spectroscopy) to visually identify the amount, shape, composition, and wear severity of the particulate in the sample. This method and its benefits are well documented for oil analysis, and have similar benefits for properly obtained grease samples. The key difference for greases is that it is necessary to understand that wear levels are cumulative during the operating life of the grease, and that relative quantities of observed particulate can be misleading, if comparing samples with significant differences in service time for the grease.

Patch Microscopy

When the particles of interest are non-metals or non-ferrous metals, there may be some advantage to preparing a Millipore patch by drawing a diluted sample under vacuum through the patch and microscopically analysing the particulate content to identify the presence of wear or contaminant particles, and relatively quantifying their presence. Often, this test is more difficult with greases than oils, because of the difficulty in completely dissolving grease thickeners sufficiently to pass through the patch. Solvent selection is critical, and some grease thickener types do not perform well in this

test, with the presence of thickener fibers dominating the filter patch and obscuring other particulate.

Grease Rheology

Use of a rheometer and evaluation of such parameters as normal force measurement and apparent viscosity can be significant in the characterization of grease properties. Prior research [1,2] has indicated the value of applying rheological measurements to both new and used greases, and research is ongoing to optimise this analysis and relate measured parameters to changing physical properties. Rheological measurements provide insight on changes due to incompatible grease mixing, excessive grease working, and severe oxidation. One of the capabilities of this testing is the ability to evaluate the compatibility of mixed greases. In Figure 14, a mixture of two NLGI Grade 2 greases shows an oscillatory stress value of 142 Pa. However, the baseline for the grease designated for this application, seen in Figure 15, has an oscillatory stress of only 81 Pa. This 80% increase represents an unacceptable change in the properties of this grease and shows that they are not compatible in this application. The data results of this test provide insight into grease pumpability, shear characteristics, and the tendency for a given grease or grease mixture to undergo “channeling” or “tunneling” in bearing and gear applications.

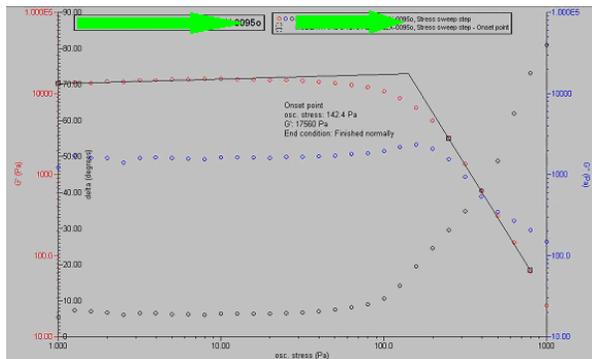


Figure 14: Oscillatory stress measurement of mixed greases with cone and plate rheometer

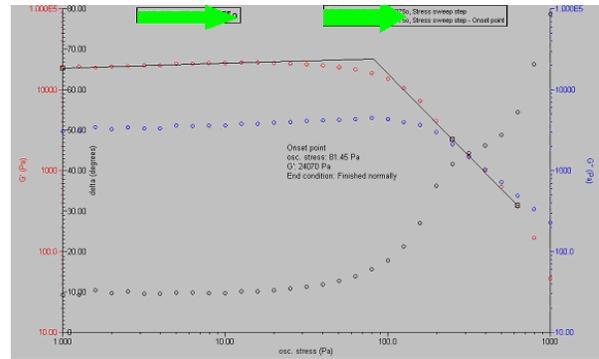


Figure 15: Oscillatory stress measurement of reference grease with cone and plate rheometer

5. Wind Turbine Applications

Wind turbines are part of a growing industry of renewable energy. Certain regions of the globe are particularly suited to deploy wind turbines to capture this energy source, and they are appearing in ever growing numbers. Much of the focus to date has been on the transmission gearbox, an oil lubricated speed increaser that takes the relatively slow rotational speed of the turbine blades and converts it to a sufficiently higher speed for the generator. While it is appropriate to focus on the transmission, it is by no means the only lubricated component where reliability is a concern.

There are no fewer than 6 major grease lubricated components in the majority of large wind turbine designs currently dominating the market. They include two grease lubricated gearsets, the pitch drive gears and the yaw drive gears, as well as the main bearings, generator bearings, pitch bearings and yaw drive bearings. For each of these grease lubricated components, failure to function can either interrupt completely, or significantly impact the efficiency and capacity for electric generation. Therefore, a solution to the grease sampling and analysis challenges present in the wind turbine can have a significant financial impact through the early detection of abnormal wear, or the identification of degraded or contaminated grease lubrication.

For open gears, the collection of a sample is best accomplished with a kit that utilizes a spatula-like tool to enable the sampler to gather the grease from the gear teeth. Since one of the important considerations is a streamlined analysis process to ensure cost-effectiveness, the gathered sample is transferred to the grease sampler

device that has been described, by means of a simple syringe. Because a non-newtonian fluid like a grease can be difficult to move under vacuum (may be insufficient to reach the yield stress for flow), the syringe plunger is

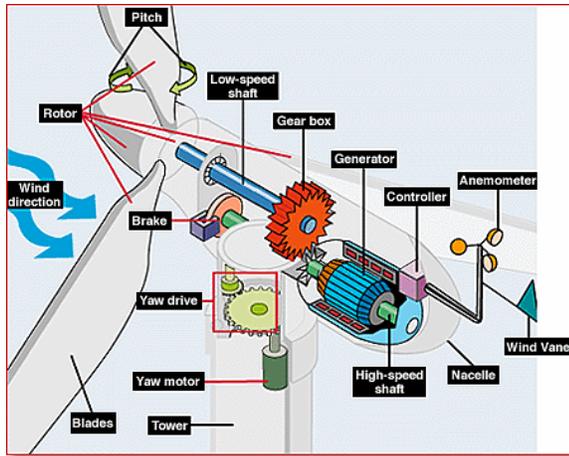


Figure 16: Components of typical wind turbine, showing grease lubricated gears and bearings (US Dept of Energy)

removed from the body by completely pulling the handle back and out, and the open body is packed with grease using the spatula. The plunger is re-inserted, and the grease can be easily moved while under pressure, to fill the grease sampler. The laboratory will now have a standard geometry, sample size and presentation for the streamlined analysis techniques described earlier.



Figure 17: A Type II Grease Thief is prepared on a T-handle extension to obtain a main bearing sample from the purge drain. (Oelcheck Labs, Germany)

For bearing locations, the same spatula kit can be used, or for enclosed locations with a sufficient access hole, a second type of sampler with a long-handled extension tool may be even more effective. This device allows the device described in Figure 3 to be inserted into the T-handle as shown in Figure 4. A drain or access plug is removed, and the assembly is inserted either a set distance into the opening, or until the stinger probe on the front of the fitting contacts the bearing surface.



Figure 18: The full Grease Thief is removed from the drain of a 2MW wind turbine, and can be submitted for streamlined routine analysis for grease and bearing condition assessment. (Oelcheck Labs, Germany)

The sample can then be cored from this location by sliding the outer tube forward, providing a sample that is proximal to the wear generation surface, and avoids collecting grease which may not be representative of the current wear condition, or the condition of the grease currently providing lubrication to the bearing (Figure 17, 18). With these new methods, reliable samples and cost-effective analysis solutions will provide insight into the operational condition of the critical grease-lubricated components of the wind turbine, and contribute to a condition-based maintenance strategy, as well as opportunities to diagnose and correct degradation root-causes to extend and optimize the life of wind turbines.

6. Other Applications

In addition to the gears and bearings in the Wind Turbine applications, other applications also provide potential for cost benefits through routine analysis. Robots have, in

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