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I. Nomenclature

v	Kinematic Viscosity (m^2/s)
μ	Absolute Viscosity (kg/m s)
AV	Acoustic Viscosity
ρ	Density (kg/m^3)
γ	Specific Gravity (N/m^3)
P_{loss}	Power Loss
f	Frequency (Hz)
λ_{exc}	Initial Emission Wavelength (nm)
λ_{em}	Initial Excitation Wavelength (nm)
Δλ	Wavelength Difference (nm)
α	Oil Parameter 1
β	Oil Parameter 2

II. Introduction

Ensuring reliability in the wind energy industry is often difficult due to the stochastic nature of the resource, the isolated locations where the plants are built and the complex forces which interact in unexpected and damaging ways[1]. These conditions have led to high failure rates for various different components in the turbine with the gearbox being the most problematic for various reasons[2,3]. Figure 1 shows the failure frequency and downtime of different wind turbine components. Whilst the failure rate is lower than most components, the downtime is far greater. The component itself is expensive so repairs or replacements within the operational lifetime will impact the operational economics of the wind turbine. An £800 bearing could fail, leading to the replacement of a £300,000 gearbox with a £50,000 per day hired crane, excluding the costs incurred from downed electricity production[4,5]. These problems will be exacerbated when more wind farms are located offshore[6] due to the more isolated conditions. One method to improve reliability is to monitor the condition of components in the wind turbine using sensors which measure different variables. Using this data with statistical methods, the current and future condition of components may be accurately assessed[7]. According to McMillan and Ault, it is envisioned that this will reduce failure rates, allow an efficient maintenance regime to be established and reduce overall costs that are incurred due to downed wind turbines[8].

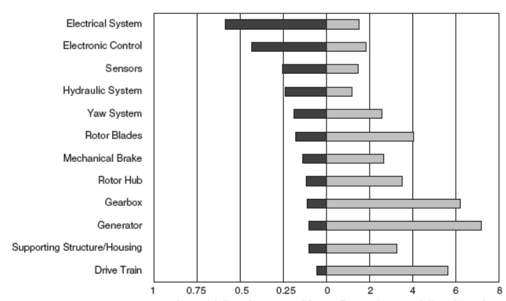

Figure 1: Failure frequency and downtime for wind turbine components[9]

The gearbox is an ideal component to monitor for several reasons. The gearbox is responsible for many of the maintenance costs due to repairs, replacements and turbine downtime. A major indicator of the gearbox condition is the state of the gearbox lubricant[10]. In contact machinery, materials begin to wear and ultimately break depending on the types of loads that are applied. These wear particles are often liberated and become suspended in the oil which can then be analysed[11]. Since the majority of materials in a gearbox are metallic, most online systems of detection have relied on identifying changes in electromagnetic properties of the oil[12].

However the main problem is interpreting what these changes actually mean. In order to establish an effective maintenance regime, there must be a high degree of certainty which particular area is problematic[13].

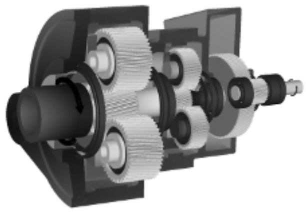

Figure 2: Computational model of a planetary gearbox[14]

As well as identifying particles suspended within the oil, the quality of the oil itself is crucial to the operation of the gearbox with the rate of degradation being affected by several different factors including temperature, oxidation, contaminants and time[11]. Modern lubricants for gearboxes include many different additives to alter chemical properties which are vital to the operation of the gearbox[15]. Any small change to the chemical composition of these mainly synthetic oils may have disastrous results and so constant monitoring is required to give wind turbine operators advanced warning of any problems.

There is currently a large variety of technology already available for these purposes, however most are offline systems and the effectiveness of each varies. The purpose of this review is to present the current technologies that could be applied and provide recommendations for a wind turbine gearbox online/inline CM solution.

III. Oil Analysis

1. PHYSICS AND CHEMISTRY OF OIL ANALYSIS

There are several factors that affect the properties of lubricating oil which can be monitored to give an indication of its condition and allow predictions to be made about its future performance[16]:

- Acid Content
- Viscosity
- Water Content
- Oxidation Level
- Temperature

Several interdependencies exist between these parameters such as oxidation and acidity levels. Ideally, any new remote CM system would have to track all of these properties to effectively evaluate the current and potentially predict the future state of the lubricants in the gearbox. It could be argued that acidity and water are the most important as these will give provide data on the potential corrosion state of gearbox components[17]. However, acidity is closely related to oxidation and so it may be argued that it is equally important.

2. POTENTIAL TECHNOLOGIES

A. *Infra-Red Spectroscopy (IRS)*

IRS operates on the principle that chemical bonds will absorb a unique wavelength of infrared radiation corresponding to their resonant frequency[18]. This is the frequency at which a particular mode of the molecule will vibrate at, very similar to the frequencies associated with structural modes of buildings. Figure 3 shows the first 3 modes of a simple molecule.

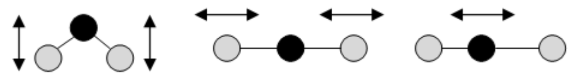

Figure 3: First 3 vibrational modes for a simple molecule[19]

Absorption IRS is the most common method used to identify molecules. In its simplest form, a beam of monochromatic IR radiation is directed at a reference sensor to detect the wavelength emitted[20]. The same beam is then directed at the sample with a sensor positioned underneath that will detect if the beam passes through or has been absorbed and the process is repeated for the desired range of IR wavelengths. The main problem with this method is the length of time it requires to analyse all the desired wavelengths. The process may take up to 10s[20] to analyse the sample fully. However, Fourier Transform Infrared Spectroscopy (FTIR) may also be used. Instead of using a monochromatic source, a beam consisting of a range of wavelengths will be passed through the sample and the values of wavelength which are absorbed are recorded by the sensors[20]. This process is repeated using different combinations of wavelength values in order to establish separate data points which can be interpreted using Fourier mathematics, reducing analysis time to between 0.25 - 1s[20].

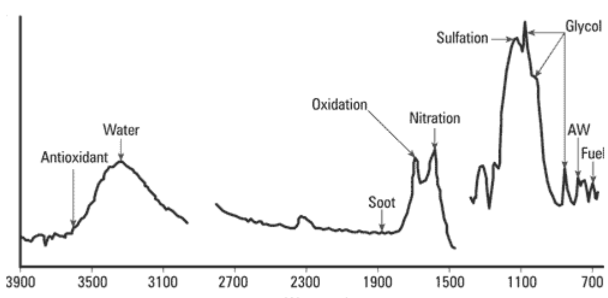

Figure 4: Amount of IR radiation absorbed for each particular component of a sample[21]

FTIR can determine the level of oxidation by identifying carbonyl (C=O) due to its unique bond absorption wavelength. The wavelength which will be absorbed by this bond is approximately 6300 nanometres (nm)[22]. In this region, IR energy is absorbed by the carbon-oxygen bonds in the oxidized oil and very few compounds found in petroleum lubricants have significant absorbencies in this area. Monitoring this region is a direct measurement of the oxidation level. However FTIR does have problems. In complex liquids such as lubricating oils, there are a variety of polymers, bonds and vibrational modes which are affected by temperature and contaminants.

Another benefit of using IRS is water can be identified simultaneously with other chemicals related with lubricants. However the ability of FTIR to detect water particles starts to diminish below a concentration of 500ppm in synthetic oils[23]. Figure 4 shows the detection of various chemicals in an oil sample. Oxidation has a defined peak, indicating precise detection capabilities whilst water has a broad peak, indicating uncertainty, especially when smaller concentrations are analysed.

There is high potential in developing FTIR as an online/inline sensor system. There are currently commercially available hand held IRS devices such as the Spectro FluidScan Q1000® which has the ability to measure TAN, TBN, oxidation, nitration, sulfation, glycol, water and glycerine within 1 minute[24]. Whilst the cost is high and no remote application has been tested, there is a possibility of creating a miniaturised IRS sensing system. The main problem is the ability to detect water since most portable commercial IRS operates with 100 ppm as the lowest detection level.

B. *Photoacoustic Spectroscopy (PAS)*

Light is absorbed by a sample which causes a change in the thermal energy structure of molecules. Eventually the sample would return to its original energy state due to heat transfer with the surrounding environment. The process of hitting the sample with light can modulated, so that there is a cycle of energy absorption and emission. This cycle of modulated light can be increased so that the sample does not have time to expand and contract to the modulated light source, resulting in a change in pressure which causes an acoustic wave that can be detected with hyper sensitive microphones or piezoelectric devices[25]. Figure 5 shows the layout of a PAS sensor.

In standard PAS, the modulated light source is usually a high powered xenon or halogen lamp which is passed through a monochromator to allow selection of the desired wavelength of light[26]. If the sample absorbs a particular wavelength, the molecules will become excited and then relax, generating heat. This occurs for every cycle of modulated light that hits, resulting in a series of thermal waves that travel through the sample until reaching the surface. At this point the heat is transferred to the contacting gas as an acoustic wave which then travels to the microphone. Individual chemicals and elements are identified by the amplification of this sound.

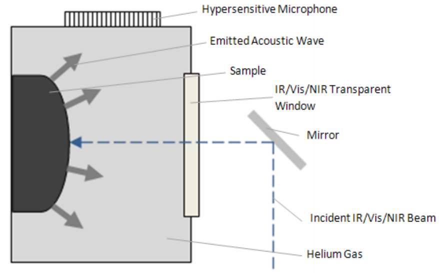

Figure 5: Diagram of classic PAS sensor equipment[27]

Compounds that have a higher absorption coefficient will generate a wave with greater amplification. To fully analyse a sample, a range of monochromatic wavelengths can be used. Since PAS analyses the thermal waves that generate acoustic waves, it is unaffected by surface scattering effects unlike other types spectroscopy. This allows the analysis of oils which have suspended solid particles. PAS has the ability to detect trace levels of water within a sample (≤50 ppm) in petroleum oils[27] which is very desirable in the context of gearboxes. However these detection levels have so far been only achieved as an offline experimental system.

The potential to develop PAS as an online sensor is high. There is currently significant research into miniaturising the technology, with sensors cells ranging in size from 5mm^2 to 500 mm^2 that can be integrated as part of a remote system[28]. The accuracy of miniaturised devices for detecting the desired oil parameters has not been established.

C. *Solid State Viscometer*

Solid state viscometers measure the acoustic viscosity of a given sample using the properties of shear wave propagation. A shear wave is a type of energy transfer through a material, where the direction of wave propagation is perpendicular to the direction of motion. Figure 6 shows how a shear wave propagates through a material.

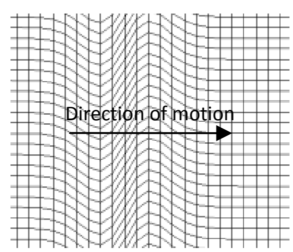

Figure 6: Distortion of material due to movement of shear wave

These waves can move through most materials but changes occur when the wave transfers between materials. At the transition point, energy that is lost from the wave which is directly proportional to the frequency of the wave, the density of the new material and the absolute viscosity of the new material. Equ (1) shows the relationship.

$$P_{loss}^2 \sim f \times \rho \times \mu \quad (1)$$

If an acoustic wave resonator is placed in contact with a lubricant and a low frequency shear wave is transmitted through it, a layer of the oil will hydrodynamically couple to the surface of the resonator. If the frequency and amplitude of the wave is fixed (frequency is set by the design of the sensor and the amplitude is set by the power of the electrical signal sent), the layer thickness and energy dampening (power loss) will be determined by the viscosity and density.

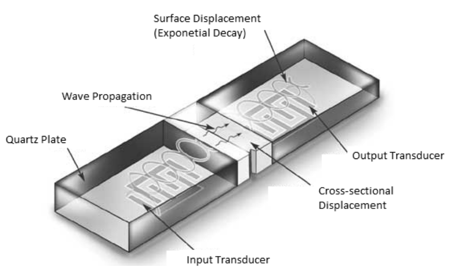

Figure 7: Layout of acoustic wave resonator sensor[29]

The oil is not adversely affected by the process as the area which forms the hydrodynamic coupling in the micron scale. As mentioned previously, it is essential to report the temperature of the oil sample before an assessment of the viscosity can be made.

There is high potential to develop a solid state viscometer as an online or inline system. There are currently several sensors designed for this purpose that have high correlations between data measured using AV and laboratory tested samples using conventional methods[29]. Since it is not standard practice to state the acoustic viscosity of a sample, a conversion must be made to either kinematic or absolute viscosity. A critical area of these sensors is establishing a relationship between these measurements as it will change depending on the type of oil that is being analysed[29]. In addition, the sizes of these sensors are small, measuring approximately 12 to 24 cm^3 which would be ideal for integration into a wind turbine gearbox. The accuracy of solid state viscometers in analysing lubricants for gearboxes would have to be investigated further to ensure additives, vibrations in the nacelle and temperature variations do not have adverse effects on measurements.

D. *Fluorescence Spectroscopy*

Fluorescence spectroscopy uses light to excite electrons that then emit electromagnetic radiation which is detected by a spectrometer. The wavelength emitted and its intensity is characteristic of the molecules present and their amount in the sample. A wavelength of light is selected to excite the sample using a laser or using a halogen lamp can be combined with a monochromator. The light hits the sample, causing an increase in the energy of the molecule which results in a vibrational mode[30]. The molecule then drops back down to its ground state, releasing photons of a particular wavelength in the process. The wavelength emitted is dependent on several factors such as the molecule structure, its vibrational modes and the surrounding molecules.

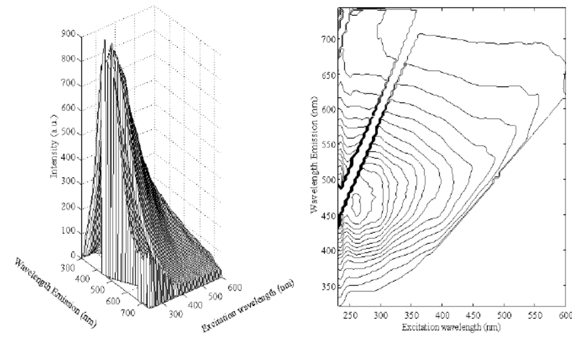

Figure 8: Total Fluorescence spectra of a crude oil sample[31]

There are two main methods of analysing the sample. The first is to use Total Fluorescence Spectroscopy (TFS), where the sample it hit with one wavelength of electromagnetic radiation and all emitted wavelengths are measured. This process is repeated for different excitation wavelengths until a full profile is created. The data is presented as a 3D plot of excitation wavelength against emission wavelength with fluorescence intensity as the z-axis or as a 2D contour plot, as shown in Figure 8. The main disadvantage is that Raman and Rayleigh scattering of the excitation light can cause false signals[31]. The excitation light wavelength is reflected and then detected by the spectrometer, giving an inaccurate emission spectrum. It is necessary to remove these as shown in 2D contour diagram in Figure 8.

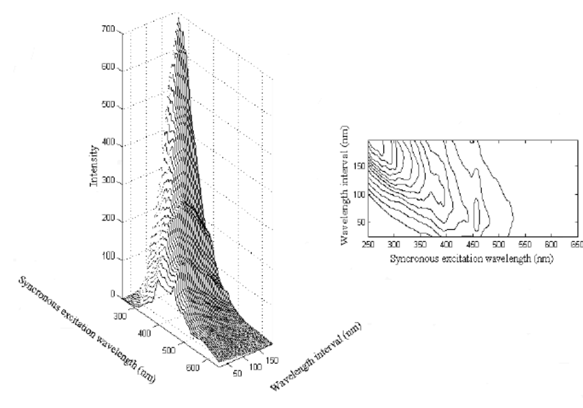

Figure 9: Synchronous Fluorescence spectra of a crude oil sample[31]

The second method is Synchronous Fluorescence Spectroscopy (SFS). This combines two different methods of fluorescence spectroscopy into one analysis. The first is to use an emission spectrum where the sample is analysed by using a beam of monochromatic light and measuring the resulting emitted wavelengths. The second is to use an excitation spectrum where the sample is analysed by hitting the sample with different wavelengths of light and measuring the emission of a single wavelength of light. SFS combines these by setting an initial emission wavelength (λ_{exc}) to bombard the sample and an initial excitation wavelength (λ_{em}), with $\Delta\lambda$ being the difference between λ_{exc} and λ_{em}. $\Delta\lambda$ is varied after each bombardment and a similar 3D plot to TFS can be created. The main advantage of SFS is clearer spectra when compared to TFS due to the reduced effect of Raman and Rayleigh scattering. Figure 9 shows the spectra obtained from SFS.

There is high potential to develop fluorescence spectroscopy as a sensor system. Experiments have already been conducted demonstrating its ability to analyse lubricants from oil sumps[32]. Oil degradation was not classified by individual parameters, but an overall change in the condition over time. Similar studies have shown its use for identifying various different products of petrochemicals with similar composition to synthetic lubricants[33].

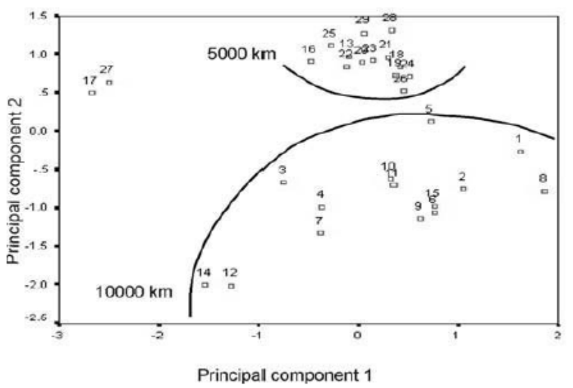

Figure 10: PCA of data from samples taken at 5000km and 10,000km[32]

In Figure 10, Principal Component Analysis (PCA) of samples is shown. This method is used to analyse multivariate data by changing a set of correlated variables into smaller components which are easier to interpret.

In addition, there have been recent developments of low cost integrated fluorescence sensors at University of Edinburgh[34]. The main problem is achieving significant accuracy identifying key lubricant parameters. It is likely that fluorescence spectroscopy would not be used as an individual system but would be combined with other types of spectroscopy such as absorption as described by Mignani et al[35].

E. *Electrical Conductance*

As the concentration of water varies in lubricants, its electrical resistance will also change. A gearbox lubricant has its capacitance tested for different percentages of water saturation. Once this has been established, an electrical probe is used to constantly measure the electrical of an oil supply channel and any change to the capacitance can be interpreted as a change in the water content.

The potential to develop electrical conductance as a sensor is high but is unlikely to provide any significant information about the oil. Several factors can affect the electrical conductance of lubricants. It may be useful to incorporate into a sensor system to augment data collection.

3. *POTENTIAL SOLUTIONS*

Out of the current technology that can identify parameters in gearbox lubricants, there are several that can potentially be adapted as cost-effective, compact and robust remote sensor for wind turbine gearboxes.

Fourier transform infra-red spectroscopy is one of the potential solutions. As mentioned previously, it has potential to detect various parameters such as TAN, TBN, oxidation and water content by analysing the amount of infrared radiation that is absorbed from an oil sample. The concept is relatively simple but difficult to adapt into a sensor. One method could be to use optical fibres to transmit the IR source to the desired analysis location[36]. There is a large range of commercial optical fibres used specifically to transmit IR radiation. Each is made of a specific material such as fluoride glass, single crystal glass fibres or chalcogenide glass[37]. When selecting optical fibre for radiation transmission, it is important to understand the wavelength attenuation spectrum. As shown in Figure 11.

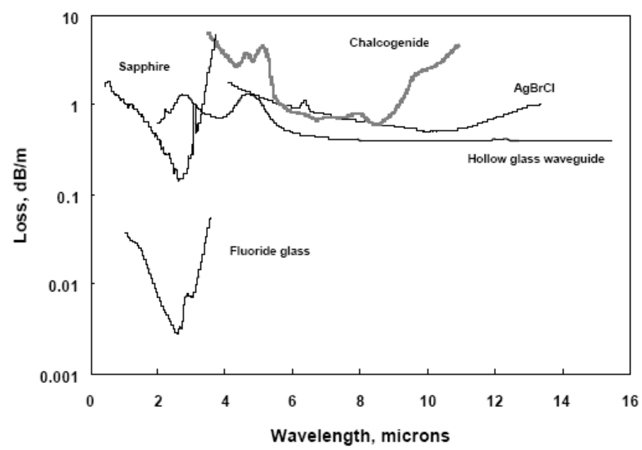

Figure 11: Attenuation spectra for different IR fibre optics[37]

With the presence of impurities and specific material properties, certain wavelengths of IR radiation are absorbed or scattered by the optical fibre. The importance of this effect depends on what is being analysed. As mentioned previously, there are certain compounds which need to be identified to assess the quality of the lubricant. Ideally optical fibre should transmit all wavelengths that would be absorbed by these compounds to allow accurate analysis. However in reality this may not be possible. As an example, carbonyl (C=O) strongly absorbs IR radiation between 1670 to 1820 nm[22]. If fluoride glass optical fibre was used, it would attenuate the signal at this waveband significantly. This would give a high evaluation of carbonyl groups, possibly leading to the false conclusion that oxidation levels are high. Fortunately there are a wide range of fibres with different wavelength attenuation ranges. It would be necessary to adopt several different types of fibre to ensure transmission of characteristic wavelengths. FTIR will only be able to be developed as an online sensor solution since the analysis process requires different groups of IR radiation to hit a sample. This means that the sample would have to be removed from its lubrication channel, hit with a series of wavelengths and then allowed to re-enter. The analysis itself takes only 0.25 to 1s but is still long enough to prevent inline development. FTIR's main weakness is the inaccuracy in detecting water below 100 ppm. To improve upon this, there are two potential approaches. The first is to concentrate on improving absorption detection. This will be highly problematic as the water and oil both absorb a large range of IR radiation, giving ambiguous detection signals. The other solution is to develop a second sensor to compliment FTIR. This could be another absorption spectroscopic method as described by Mignani et al[35]. In this process, the information obtained from two or more different methods would be used in multivariate data processing to achieve higher accuracy[38].

PAS is another potential solution. The main reason for this is the extremely low water detection limits which have been demonstrated by Foster et al[27]. In this method, PAS was able to detect not only free water below 50 ppm but also methanol and other groups which contained the hydroxyl group by using an excitation wavelength of 2930 nm. The precise excitation wavelength depends on the type of oil that is being analysed and can be established by using FTIR spectroscopy. This is required as water has high absorbencies between 2700 and 3200 nm, depending if the water is free, contained in an oil matrix and the type of lubricant. Each time, it is necessary to determine the approximate water absorbency wavelength which would then be used by PAS to excite the sample. Considering the advantages offered by PAS in detecting water and its potential relationship with FTIR, it is recommended that these two methods are used to complement each other in a CM system

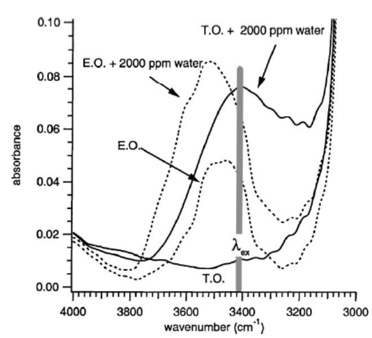

Figure 12: Use of FTIR to determine excitation wavelength for PAS sensor[27]

Fluorescence spectroscopy (FS) is also a potential solution for lubricant quality analysis. The main advantages of FS as a sensing system include few spectral interferences and a wide analytical range[39]. This means that signals generally are representative of the presence of a compound rather than scattering or another anomaly. Changes in oil quality have currently been limited to assessing differences between emission spectra rather than individual characteristics, as shown in Figure 13. Whilst this data would not be particularly useful for wind turbine gearbox analysis, it can be used in conjunction with other sensors such as FTIR and PAS. Developing FS as a sensor is also possible. As demonstrated by Liang et al at the University of Manchester, it is possible to use FS as a small online sensor that utilises detailed data analysis techniques to establish the condition of engine oil[32].

The main disadvantage has been insufficient excitation of the sample, leading to low fluorescence emissions and poor detection[32]. It is recommended that FS is used as part of any oil analysis system due to the potential for miniaturisation and multivariate data analysis. In addition, FS may be used in identification of certain particulates suspended in lubricating oil.

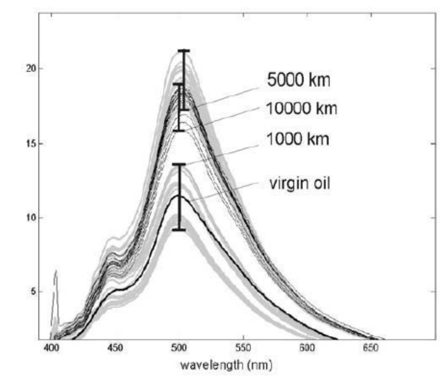

Figure 13: Fluorescence spectra from oil samples at different mileages[32]

Finally the last technology that is suitable for a gearbox CM system is solid state viscometers (SSV's). The main reason for its inclusion is the ability to measures viscosity directly. FTIR, PAS and FS cannot determine viscosity, although they may be able to give indications on the potential viscosity state. However any value obtained is likely to be inaccurate and so it not recommended.

IV. Particulate Analysis

1. PHYSICS AND CHEMISTRY OF PARTICLUATES

A. *Source and Composition*

Particulates suspended in lubricating oil originate from a variety of sources. In terms of a wind turbine gearbox, the vast majority are wear particles which have become detached from different gearbox components. Since there are no combustion engines, relatively few other particle contaminations such as soot are found within the oils. The surrounding environment may have an effect on additional contaminants. By analysing the elemental composition of the particulates, it is possible to identify their potential source.

B. *Type of Wear*

Wear particles can also indicate the degree and type of damage that is being experienced by different gearbox components. The size and shape of particles are dependent on the type of erosion they have experienced whilst the number can signify the degree of damage that has occurred.

- Rubbing Wear
- Cutting Wear
- Spherical Particles
- Severe Sliding
- Bear Wear Particles
  - Fatigue Spall Particles
  - Laminar Particles
- Gear Wear
  - Pitch Line Fatigue Particles
  - Scuffing/Scoring Particles

C. *Number of Particles*

The number of wear particles is a great indicator of the state of the gearbox. However as a single parameter, it can only indicate that a fault is occurring, not the location or degree of the fault.

2. *POTENTIAL TECHNOLOGIES*

A. *Ferrography*

Traditional ferrography is a process that separates magnetic and non-magnetic particles from oil and then uses an optical sensor to analyse them. The first stage is to create slides called ferrograms (see Figure 14) for observation. The oil sample is diluted and allowed to flow down the ferrogram that is at an angle and has a magnetic cylinder underneath. The angle means that the magnetic field experienced is weaker at the start and stronger at the end. This causes larger ferrous particles to deposit at the start and smaller ferrous particles at the end.

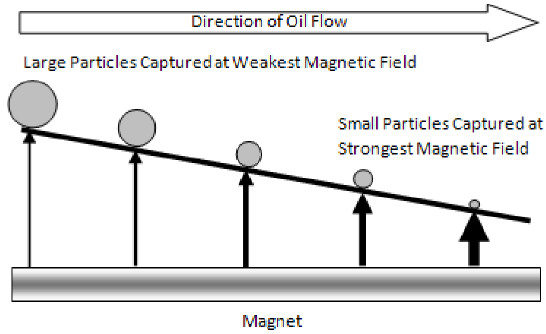

Figure 14: Operation of a ferrogram

Non-ferrous particles are deposited on the slide at locations depending on the concentrations of ferrous particles. If there were no ferrous particles in the sample, relatively few non-ferrous particles would be captured in the ferrogram despite high concentrations in the sample. A reflecting red light source is situated above the sample and a green transmitting light source is situated below. A digital camera is used to take images that can then be classified. The final stage is to heat the slide to 320 °C to distinguish between different particle types.

The categories of particles used by technicians are summarised in Table 1. In addition, the size and shape of particles can also be classified.

Non-Ferrous	*Ferrous*
White Nonferrous Particles	High Alloy Steel
Copper Particles	Low Alloy Steel
Babbitt Particles	Dark Metallic Oxides
Contaminants	Cast Iron
Fibres	Rust (Iron Oxides)

Table 1: Categories for non-ferrous and ferrous particles

There is high potential to develop ferrography as a sensor. Online ferrographs have been created recently which use optical image processing in order to identify particles[40,41], removing the need for an analyst. Currently accuracy and reliability depend on many different factors such as the flow rate of oil, the magnetic field strength and the distribution patterns of deposited particles. Despite this, the research is promising and also demonstrates the ability to miniaturise the technology, a key requirement for wind turbine nacelles.

B. *Fluorescence Spectroscopy (FS)*

FS used extensively to identify iron, molybdenum, and copper wear particles in jet engine oils[42]. According to Aucélio et al, detection limits in the order of µg/g were of these elements**Error! Bookmark not defined.**. However determining nickel and chromium are far less accurate due to band structuring and continuous background[43]. Sample preparation is not required but atomisation is, usually by means of a graphite rod. Only small samples are required to take accurate measurements, therefore the system may be considered as non-destructive. There is high potential to develop FS as an online particulate sensor, especially as the system is effective at assessing oil quality parameters.

C. *Particle Counters*

Particles counters are used to quantify the amount of wear that is present in a lubrication channel. This is achieved by measuring different physicals features of the particulates. One standard method is to use a laser beam with a uniform intensity to pass light through an oil channel[44]. This light is detected at the opposite side by a photo diode that gives a variable voltage signal (see Figure 15). If a particle passes between the laser and the diode, the value of light falls, resulting in a voltage drop. This means the voltage can be correlated to the size of the particle. For a given lubrication channel, it is possible that there will be many hundreds of particles passing at a certain point, spread across the cross sectional area.

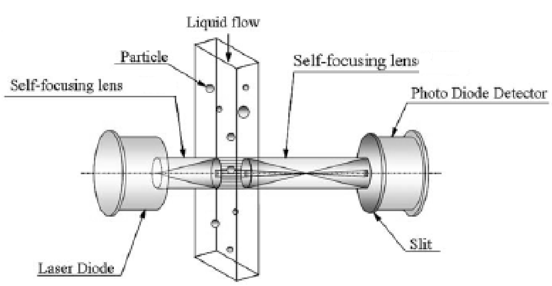

Figure 15: Operation of a particle counter[44]

Optical counters identify the size and shape of particles by analysing the voltage pulses that are generated by the photo diode. The shape will affect both the duration of the pulse and the amplitude of the voltage spike. A relationship between the voltage spike and the area must be calibrated before accurate measurements can be taken. Estimating the thickness of the particles is necessary as the system can only identify particles in 2D. Another relationship between the diameter and the thickness must also be developed for the particles that are expected to be found in the machine. The machine cannot be used to identify the material composition; it is only used to determine the number of particles and their size present in a lubricant. Additional equipment would be needed to analyse the elemental composition.

There is significant potential to develop optical particle counters as an online system for wind turbine gearbox analysis. There is currently a large range of commercial particle counters designed for this purpose[45]. In addition, several research and industrial groups are conducting research into improving the accuracy of these devices. The equipment required for the sensor is low cost and also can be miniaturised for the purposes of the wind energy industry. Future research should consist of integrating the sensor with technology that identifies the composition of the particles to allow greater understanding of the gearbox's state.

D. *Electromagnetic Detection (EMD)*

There are a variety of EMD methods which are used in detecting metallic wear and other parameters in oil in lubricating oils. Currently, it is the most popular technique for online/inline lubrication condition monitoring in the vehicle and manufacturing industries

1) Induction Factor

Induction involves measuring the change of a magnetic flux field as particles enter. Typically, an inductive coil is placed around a tube or container to create a magnetic field through which the fluid passes. By using electronic circuitry and software, it is possible to neglect signals from air bubbles. Induction sensors can also differentiate between ferrous and non-ferrous debris. Metallic particles have higher conductivity than oil, resulting in increases in current proportional to the quantity and type of material. Currently, induction sensors are commercially available from manufacturers such as MACOM™ [46]. Miniaturisation of the technology has also been demonstrated[47].

2) Dielectric Constant (DEC)

A dielectric is an insulator and the constant is the rate of electric flux density produced in a material to the value in free space provided by the same electric field strength. This technique is able to detect when a change has occurred in the oil. Wear debris can be detected in this manner but only in a generally sense: material composition and wear type cannot be determined to any degree of accuracy. Changes in chemical composition can affect the DEC, further diminishing its wear analysis capabilities. However due to the cheap, robust nature of the technology, it is often used to monitor the general condition of lubrication oil[48].

3) Dielectric Loss Factor (DELF)

DLF (or TanDelta) increases strongly with polar contaminants such as water, glycol and oxidation products. Metallic debris and soot also increase the tandelta. It also has a greater dynamic range when compared to the dielectric constant and is more sensitive to the oil condition. It is currently used in vehicle lubrication condition monitoring to indicate abnormal conditions.

4) Magnetic Flux Constant (MFC)

The concentration of ferromagnetic particles is estimated by means of a fixed magnetic field. The field collects the particles and the field is likewise modified by the presence of the particles. This change in the magnetic flux is monitored and can be converted to the ferromagnetic particle concentration by means of an algorithm. Other elements such as nickel and molybdenum cannot be detected potential use of MFC as a CM sensor.

5) Electric Filters

Ferromagnetic particles are attracted to an electric grid or plates which serve as opposing electrodes. Current flow between the electrodes signals the presence and general concentration of conductive magnetic particles. Depending on the design, the spacing of the grid/plates and a time-sequence can be used to estimate particle size and concentration of wear debris in the oil. This technology is commercially available from HVDACLab and it used in the wind turbine industry[46].

3. POTENTIAL SOLUTIONS

Currently there is no single technology which can accurately count, quantify, categorise and identify elemental composition of particles suspended in oil as part of a low cost, online/inline system. However there is a wide range of technologies which can fulfil some of these criteria and there is significant potential for integrating them into one system.

Since the elemental composition of the gearbox is known, a list of potential particulates can be established. This allows sensors to be developed that can selectively identify certain elements and compounds such as iron, nickel, chromium and molybdenum. There are also several types of effect that can be observed to identify particles. Each element or molecule could have a laser diode emitting light corresponding to its characteristic wavelength, allowing selective identification. Emission of certain wavelengths could be observed, using a light source and detector calibrated to identify unique emissions. A related method of identification is to observe any scattering effects that are displayed by different chemicals[49]. Sensors can be positioned at different angles around an oil channel to detect wavelengths of light that have been reflected by particulates. The angle and intensity at which the reflection occurs can be related to a particular material.

An optimal solution would be to use a combination of these techniques as it is unlikely that one would have the required accuracy. Data collected from one solution would be augmented from another source. Identification of particles will not depend solely on the sensing capabilities, but also on the statistical methods which will be used to interpret the information gathers by sensing devices[50]. Data collected from a cheap sensor with relatively inaccurate identification capabilities could be enhanced with data collected from a similar sensor that observes a different effect. By employing sensors in this manner, there is great potential for achieving an accurate, low cost solution to particulate identification in oil.

Fluorescence spectroscopy (FS) is an ideal solution as it can be adapted into an optical fibre sensor making it cheap and robust. Since FS is already highly recommended to analyse oil quality, it would be relatively simple to vary wavebands for particulate identification. Unfortunately exact spectroscopic analysis of samples is unlikely due to the lack of sample preparation and atomisation. However another approach may be taken. Spectra obtained from oil samples with known quantities of metallic wear can be compared to measured spectra of gearbox lubricants. Data analysis techniques would then be used to establish relationships and correlations between different aspects of the spectra. Using this indirect method, it is possible to assess the current levels of metallic wear and future trends. This type of analysis may not have the desired accuracy as an independent system. Incorporation of other technologies would dramatically reduce the errors that are expected

Particle counters also have great potential as they are commercially available devices and have demonstrated reasonable accuracy in quantifying the amount of wear in lubricants.

V. RECOMMENDATIONS

Lubrication analysis of wind turbine gearboxes poses unique challenges for developing a robust condition monitoring system. The isolation of wind turbines, both onshore and offshore, and constraints prevent the use of many standard analysis techniques for reasons of cost, size and accuracy. It is highly probable that any CM system will require new research into adapting current technology into sensors that can fulfil the criteria. This report has reviewed the various technologies that can be adapted for use in such a system. For oil quality analysis, it is recommended that a combination of Fluorescence Spectroscopy, Fourier Transform Infrared Spectroscopy, Solid State Viscometers and Photoacoustic Spectroscopy should be used with multivariate data processing. It is believed that a combination of smaller, less accurate sensors will yield adequate information to assess the current condition of the oil and the future trends. For analysing wear particles suspended in the oil, it is recommended that ferrography, particle counting, fluorescence spectroscopy and a simple electrical constant sensor are adopted. From reviewing the state of the current technology it is believed that all systems may be miniaturised and integrated into one system. Again considerable multivariate data analysis will then be necessary to evaluate the material composition, quantity and wear type.

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