Early Wear Detection and Its Significance for Condition Monitoring

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Abstract

This paper proposes the concept of how machinery condition monitoring can be taken to the next level, through micro-sensing of tribological phenomena occurring between contacting surfaces. By considering wear transitions and wear rates it is possible to distinguish between benign and potentially harmful wear scenarios. By measuring the tribological phenomena associated with these conditions, it should then be possible to determine with greater accuracy the health of a machine at any point in its life. For this approach to succeed, it is necessary to develop a comprehensive and holistic monitoring strategy and target sensing technologies for the key wear factors. The paper has two main sections. Firstly, tribological phenomena and the onset of wear which sets out why and what needs to be monitored. The factors influencing the wear process are grouped into three key areas: lubricant condition, tribo-pair condition and operating condition. Through a critical and comprehensive review of developing and state-of-the-art tribo-sensing, the second section identifies the potential technologies for monitoring or measuring the physical parameters within these three groupings and thus sets out how the next generation of machine condition monitoring will need to evolve in order to achieve early wear detection and the related benefits.

Key Words: Tribological Phenomena; Tribo-pairs; Early Wear Detection; Machine Condition Monitoring

1. Introduction

In high value and complex machines, there is always demand for improving safety and increasing efficiency and performance in order to reduce energy usage and unnecessary consumption of finite resources, for example due to premature scrappage or over-engineering. Health monitoring of machines has long been employed, but targeting more comprehensive in-operation sensing and faster autonomous data interpretation would enable earlier detection of system decay and hence improved prognostics/advisory assessment. Reducing the uncertainty in machine condition and time to failure could also be an enabler for better future designs. This is crucial to the prosperity and delivery of industrial strategies and meeting emissions and renewable energy targets across the world. It is also critical to the pursuit to safeguard high value assets and maintain their complex precision operations. To date, many methods have been employed for machinery monitoring, but few embrace monitoring of the tribological phenomena that are key to the goals outlined above, as tribological surfaces and contacts within a machine fundamentally influence operational efficiency and life-cycle performance. Hence in-situ measurements of tribological phenomena may be used to provide an early indication of wear, ahead of impending failure. However, most of the methods employed for machinery monitoring are still relatively basic and rely on detecting the secondary effects of failure, such as increases in vibration or bulk temperature. Such methods are well established and proven for detecting major physical changes associated with the later stages of machinery or component life.

Nonetheless, to improve the efficiency of machine operation and management, we need to determine the status of a machine at any time of its life. This requires detecting subtle changes in machinery health, in order to provide an accurate picture of current condition. Advanced techniques are necessary to determine the condition and tribological development of early-stage wear and thus to allow an understanding of the start of such processes. Current tribological parameters that have been measured with varying degrees of success include oil quality (pH, viscosity, permittivity, conductivity, temperature); debris; acoustic emissions; power consumption; vibration; film thickness (acoustic, optical, electrostatic). Data on these parameters are useful to show the evolution of wear.

This paper reviews the status of monitoring tribo-phenomena and identifies existing capability and gaps and discusses how these may be addressed by current technology and planned advancements.

Table 1 Functional requirements for a Condition Monitoring system, adopted from ISO-13374 [1]

Function	Examples
Advisory	Decision support and planning - prioritised operations; material/supply chain planning; maintenance/workscope planning; optimised efficiency
Prognostic	Availability - future health/capability; Remaining Useful Life (RUL); Digital Twin
Diagnostic	Current health or status - usage; BIT / fault codes; failure/fault diagnostic; RCA
State Detection	Exceedance monitoring; anomaly detection; alerting; trending; configuration; BIT; segmentation; operational regime / speed / phase
Manipulation	Pre-processing - feature or information extraction; frequency domain data; normalisation
Data Acquisition	Physical parameters (temp; speed; vibration); date / time; GPS; video; picture

The ISO framework in Table 1 provides a convenient way of defining the functional requirements of a condition monitoring system. It also highlights the sequencing of the foundational layers and the importance of getting each of these right in turn, if we are to build a successful monitoring and management strategies.

The intention of this paper is not to present new work, but to combine various technology areas into the single context of employing early detection of wear for state-of-the-art condition monitoring and to highlight areas for future research focus. The paper is structured in two parts 1) Tribological Phenomena and the Onset of Wear and 2) Tribo-Sensors and Sensing Systems. Thereby covering what changes occur on the surface/within the tribocontact and how we might measure these. It is our intention to publish a further paper which will review Advanced Analytics and Machine Learning applications for machinery condition monitoring.

2. Tribological phenomena and the onset of wear

2.1. Through life wear progression

For most mechanical systems, through life wear progression can be described by three stages - running-in, steady state (stable) and end of life. Lubricant analysis from Lockwood and Dally [2-4], for example, shows that both the size and number of debris change during wear progression, see Figure 1.

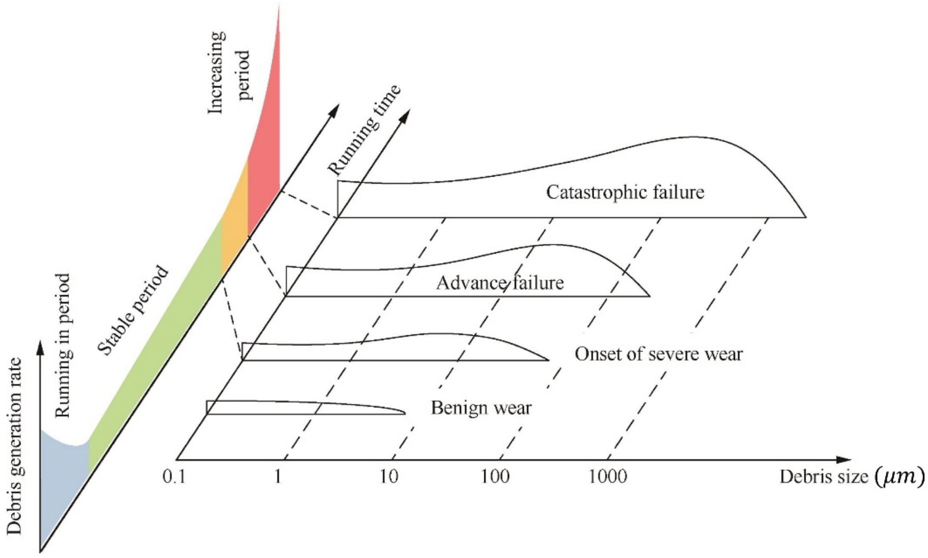

Figure 1 Relationship between debris generation (from oil analysis) and wear process [2, 3]

During early life, or the running-in stage, interaction between surface asperities or defect protrusions occurs, which leads to the plastic flow of surface peaks and asperity tip removal [2]. Running-in typically produces a lot of fine wear debris, which reduces over time as the surface asperities and defects become smoother. Any failure at this stage would be premature within the lifecycle, but could be caused - for example - by poor design, poor fitting, misalignment, overload, false brinelling or contact corrosion. After the running-in stage, protuberances at the contact surfaces have been polished by the constant passing of rolling/sliding contacts, and the machinery then enters the stable (or steady state, in terms of wear debris) phase. This phase should account for most of the machinery or component operational life and is characterised by a long period of relatively constant and low amounts of debris production. As machinery life moves into the period of increasing debris ('increasing period'), the cause of failure may include rolling contact fatigue, contact contamination by solid (wear) debris or lubrication film breakdown [5]. One of the common causes of failure in bearing rolling elements is fatigue, due to the heavy load applied in the Hertzian contact zone [6], which ultimately creates localized wear phenomena such as cracks, pitting, and spalling on the contacting surfaces. Such defects in bearings are initiated from subsurface cracks or delamination induced by surface irregularities, such as indents or micro holes, and are typically shear stress driven. These defects propagate, leading to the production of larger and greater quantities of debris and an associated rise in wear rate. The suboptimal condition of the component may also result in secondary effects such as increased vibration or frictional heating, which occur as the failure has a deleterious effect on the running of the machinery.

Wear rate is a major factor in determining the life of a mechanical system. In order to be of relevance to machinery condition monitoring and management, we need to be able to determine once the wear rate is changing aggressively i.e. as a result of incipient failure, rather than as a result of running-in or normal operation. Whilst the lifecycle of a component is understood in terms of wear rates, the actual time it takes to fail is less certain. Time to failure can vary significantly, even with similar designs and operational scenarios. It is this which sets out the design challenge to balance the need to meet operational life without overuse of resources. Hence, there is a need to find a better way to detect when and how components are progressing towards end-of-life, as opposed to exhibiting steady state behaviour.

2.2. Wear transitions and wear rate

According to Blau, there are mainly two types of wear transition; natural transition and induced transition [7]. Natural transition includes the gradual loss or degradation of material and lubricant, while the induced transition describes the acceleration of wear caused by aggressive environments for example overload, overspeed, sudden heat, stop-start.

In this paper, we use the derivative of instantaneous wear rate ($dIWR$) to distinguish between natural and induced wear transitions. In general, wear rate (WR) is defined by total measured wear volume V divided by the total sliding distance x (Eq.1):

$$WR = V/x \qquad \text{Eq. 1}$$

The instantaneous wear rate (IWR) is defined as the measurement of material loss during a small increment of operation period that occurs between intervals n and $n+1$ (Eq.2 [8]):

$$IWR_n = \left.\frac{dV}{dx}\right|_n \approx \frac{\Delta V}{\Delta x} = \frac{V_{n+1} - V_n}{x_{n+1} - x_n} \qquad \text{Eq. 2}$$

The derivative of instantaneous wear rate ($dIWR$) is given by (Eq. 3):

$$dIWR_n = \left.\frac{d(IWR)}{dx}\right|_n = \left.\frac{d^2V}{dx^2}\right|_n \approx \frac{\Delta \mathrm{IWR}}{\Delta x} = \frac{V_{n+2} - 2V_{n+1} + V_n}{(x_{n+1} - x_n)^2} \qquad \text{Eq. 3}$$

If we consider the three stages of wear progression introduced in the previous section:

Running-in - when contact surfaces are fresh and loose particles are produced by asperities deformation [9]. The WR might be high, but the $dIWR$ is negative.

Stable or steady state - after the running-in period, the machine is running in a healthy condition, the surfaces wear away slowly resulting in minimal or no increase in IWR [10]. The $dIWR$ during this stage is expected to be approximately zero.

These two periods are natural wear transitions and occur in a predictable manner.

If the $dIWR$ stays positive consistently, it is indicative of failure and the arrival of the end-of-life (i.e. third) stage. This is a result of an induced transition, as aggressive wear mechanisms (i.e. adhesion or abrasion) start to occur. If monitoring can distinguish between natural and induced transitions, an early warning of the onset of aggressive wear and its subsequent development may be possible. And it is detection of the onset of aggressive wear using tribo-sensing which could help prevent and / or enable better management of the premature failure of mechanical systems.

2.3. Factors influencing the wear process

Ludema [11] suggested that the number of parameters involved in the wear process can be extensive, with 100 variables for general sliding wear. Figure 1 illustrates the complexity of the factors potentially influencing the wear process.

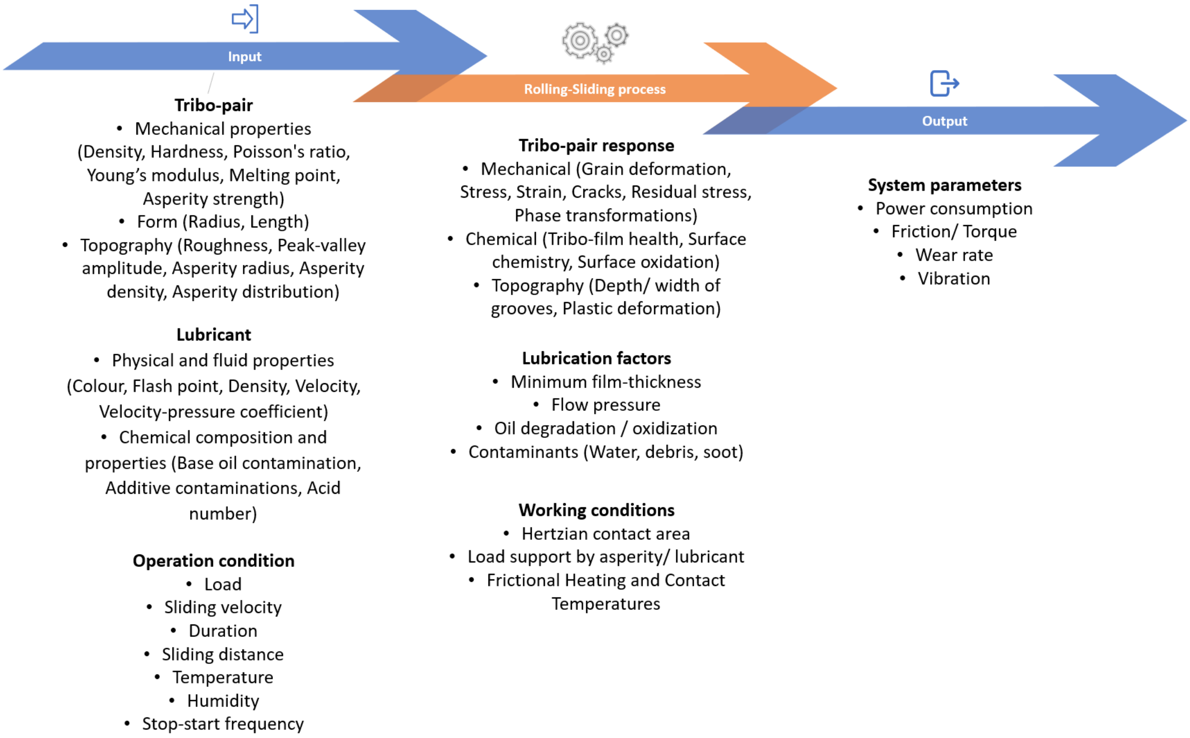

Figure 2 Factors influencing the wear process

At the input stage, there are many tribo-system parameters that may be defined or measured; notwithstanding the real interest lies in the tribo-pair response to the rolling / sliding process. What is important to consider is how this response varies depending on whether the component is in a natural or induced transition. During natural transition - either running in or steady-state - polishing of surface asperities and defects occurs producing fine wear debris, which reduces over time. Mild wear continues, the contact surface and sub-surfaces are not subject to major stresses or exhibiting deformities; the lubricant film thickness is sufficient, and the lubricant does not contain significant contaminants and / or chemical breakdown.

With the ongoing interaction of component surfaces, the material near the surface will undergo mechanical, microstructural, physical and chemical changes, which are caused by factors such as surface stresses, frictional temperature and environmental factors. A combination of various wear mechanisms leads component surfaces to deform, degrade and eventually to fail.

One of the main influences of surface wear is surface roughness: The mass loss of mild wear can be associated with global asperity height [12-14]. However, the evolution of surface roughness is the result of a combination of various wear mechanisms, including micro-pitting formed from surface material removal and plastic deformation [9, 15]; surface oxidation due to high load [16], sliding speed [17] and relative humidity [18-21]; adhesive wear due to absence of oxidation film [22] and higher energy asperity contact [23]; abrasive wear caused by large [24] and a high concentration of particles [25].

For lubricant condition, changes in chemistry, additive depletion, oil oxidation and oil contamination are all potentially significant. For the condition of the tribo-pair, tribo-film health, oil film thickness (ECR), microstructural changes such as phase changes, roughness and surface patterns (wear mechanisms), surface chemistry, surface integrity (cracks/spalls), surface oxidation, surface strain, wear depths as well as wear debris concentration (including relatively small and low volumes) should also be considered. To assess the operating conditions, and hence usage, changes in friction or torque or power consumption, load, speed, environment (temperature and humidity), stop-start frequency or transient operations and change of direction of rotation will all be important.

Thus, early indication of aggressive wear could be evidenced from combining observations and measurements of tribo-pair, lubricant and operating conditions. Comprehensive monitoring of these three areas could tell us when and where the onset of aggressive wear is occurring. Figure 2 shows the physical parameters which potentially could be monitored in each of these areas and measurement of these will be discussed in Section 3, Tribo-sensors and Sensing Systems. Not everything listed may require measurement as some are related, so by measuring one, others can be calculated or inferred

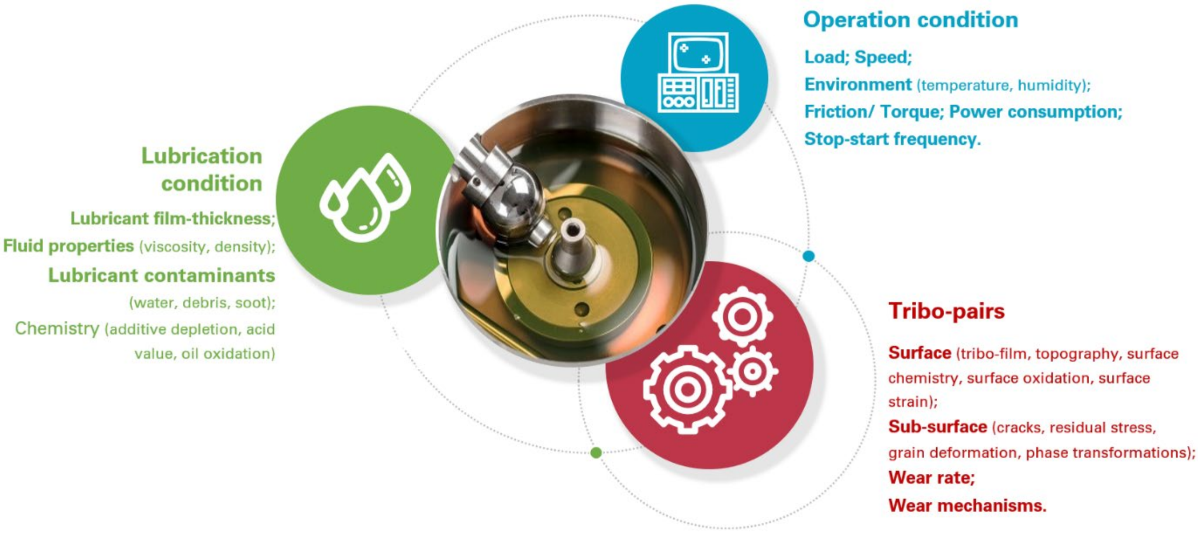

Figure 3 Physical measurements / observations relevant to early wear detection

3. Tribo-sensors and sensing systems

In the previous section, it was proposed that, in order to detect the early stages of aggressive wear, the key areas to monitor would be lubricant condition, tribo-pair and operating condition. Today, such tribo-monitoring capability is limited and little of it is in-situ and/or real-time. This section focuses on tribo-sensors and sensing systems which measure the parameters that relate to these three areas. We also discuss the relevance of monitoring the secondary effects of wear (for example vibration or bulk lubricant temperature changes).

In terms of the ISO requirements, a sensing system typically covers the initial two or three layers in Table 1 i.e. data acquisition, data manipulation and some degree of state detection. Physical sensors are generally coupled with some method of data manipulation or pre-processing, either as part of a sensing system or as established practice for feature extraction. These are the foundation of any condition monitoring system, on top of which subsequent functionality will be built: The data collected here is the input to the advanced processing stages, so it is important to make the sensing system as robust as possible. It is important to understand the physical relevance of what is being sensed to the actual condition of the machinery component(s). Features which cannot be readily linked to the underlying physics can be limited to niche applications. It is not the intention to review feature extraction methods in this paper.

It is also important to consider detection coverage (including number and type of sensors) and the frequency (both bandwidth and continuity) of data being collected. A common objective of condition monitoring is to maximize the information obtained from a relatively narrow and cost effective set of measurements [26]. Poor choices at this stage will result in reduced coverage of machinery degradation and failure modes and insufficient quality data to input to the advanced monitoring functions, which in turn will impact accuracy and responsiveness. Sub-system interactions are also important (for example shaft bearing-propeller shaft) and help inform the type and location of sensors.

The growth of global infrastructure networks, the Internet of Things, and Industry 4.0, ubiquitous communications and advances in micro-technology and low power systems means that it is becoming ever more feasible to combine the sensing element and pre-processing in one compact unit. This integrated approach is an enabler for embedding sensors into or close to the area of interest. It does also, however, require sensors that measure the parameters of interest. Operational data such as lubricant film thickness, surface roughness, friction (torque), pressure, speed or frequency, tribo-film health and chemistry, strain and temperature, wear rate, surface wear patterns and location (dimensional change) are also relevant. It is clear however that the pace of change for sensor development is lagging the ability to use such sensors effectively.

3.1. Lubricant condition monitoring

From Figure 2, for lubricant condition, the following are identified as potential targets to monitor:

- Physical Properties – viscosity, density etc
- Chemistry – additive depletion, acid value, oil oxidation
- Lubrication Contaminants – water, soot etc

There are 1189 standards (source from ASTM catalogue in Jan2021) relating to lubricants but only 47 specially focus on tribological aspects. Table 2 and Table 3 show the broad scope of real-time and off-line sensing techniques which could be used to determine lubricant condition. Whilst off-line technologies will not give a real-time indication, it is useful to understand the feasibility of what may be measured. In some cases, it is also possible that off-line techniques could be developed into on-line versions.

Table 2 Real-time sensing technologies relating to Lubricant Condition

Lubricant Condition	Physical Feature	Sensing Technique
Physical Properties	Temperature	Thermocouple [27]
		Fibre optics [28]
	Viscosity	Electromagnetic viscometer [29]
		Infrared sensor [30]
		Quartz crystal microbalance [31]
		Acoustic sensor [32, 33]
		Ultrasonic [34]
		Piezoelectric sensor [35]
	Electrical properties	Microwave sensor [36]
		Electrical resonant sensor [37]
		Conductometric sensor [38]
		Capacitive sensor [39, 40]
	Colour (RGB)	Light Dependent Resistor Sensor [30]
Chemistry	Acidity/alkalinity (TAN/TBN)	Potentiometric sensor [41, 42]
		Solid state ion selective electrode (ISE) [43]
Lubrication Contaminants	Air bubbles	Ultrasonic sensor [44, 45]
	Water	Capacitive sensor [46]
		Moisture sensor [47]
	Soot, dirt, sand, fuel	Ultrasonic sensor [34]
		Inductive contaminant sensor [48]

Table 3 Off-line sensing technologies relating to Lubricant Condition

Lubricant Condition	Physical Feature	Sensing Technique
Physical Properties	Flash point	Open/close cup methods [49, 50]

	Oil density	Mass and volume measurement [51]
	Viscosity	Capillary viscometer [52]
Chemistry	Acidity/alkalinity (TAN/TBN)	Titration [53-55]
		Infrared spectroscopy [56]
	Oxidation resistance	Rotating Pressure Vessel Oxidation Test (RPVOT) [57]

An important goal is to analyse the lubricant condition on-line (real-time) and although off-line methods such as titration and IR spectroscopy give useful information, such techniques are not candidates for embedding in the near term.

For lubricant chemistry, acidity sensors (to measure TAN) are attractive for inline (real-time) measurements, due to the propensity for oil to oxidise, particularly due to contamination by combustion by-products. Promising results were found by Soleimani [42] using thick film sensors, though the need for a reference electrode was a major challenge [43, 58]. Others have also looked at the possibility of developing acidity sensors for lubricants [41, 59], though stability and sensor performance still need to be improved. Technologies used in other industries may also offer promise. “Electronic noses” have been used to characterise edible oils and also to distinguish between waxy crude oils [60]. “Electronic tongues” [61] are widely used in the pharmaceuticals and food industries, but do not yet appear to have been tried in oil quality sensing. There is scope for developing these technologies for tribo-condition monitoring and they are candidates for small(er) scale implementation.

Optical technology for oil condition monitoring is in its infancy, but there is definite scope for measuring oil quality. For example [62] demonstrates an in-line sensor using colorimetry and reflectance techniques (similar to turbidity measurements) to relate the quality of oil to its colour. The technique is claimed to allow oxidation to be measured, amongst other parameters. The reflectance technique allows scale reduction and as such a method may well be embedded within narrow oilways or near bearings. Microwave techniques also offer an opportunity to measure acidity. In [63] a planar small scale sensor is able to detect small levels of acidity in a base oil, as well as detecting moisture.

3.2. Condition of the tribo-pair

The following properties have been identified as targets to monitor the condition of tribo-pairs:

- Surface – tribo-film, surface oxidation, topography, surface strain, wear debris
- Sub-surface – cracks, residual stress, grain deformation, phase transformation
- Lubricant film thickness
- Wear rate
- Wear mechanisms

Table 4 and Table 5 show the scope of real-time and off-line sensing techniques which can be used to determine the condition of the tribo-pair. Whilst off-line technologies will not give a real-time indication, it is useful to understand the feasibility of what may be measured. In some cases, it is also possible that off-line techniques could be developed to on-line or real-time versions.

Table 4 Real-time sensing technologies relating to Tribo-pairs

Tribo-pair Property	Physical Feature	Sensing Technique
Surface	Tribo-film	Optical/imaging method [64]
		In-situ AFM [65]
	Topography	Optical/imaging method [66]

	Wear debris (concentration, size, morphology and composition)	Resistive/capacitive sensor [67, 68]
		Ultrasonic sensor [44, 45]
		Optical/imaging method [69, 70]
		On-line visual ferrograph [71]
Surface/sub-surface	Crack/corrosion initiation and propagation	Ultrasonic reflectometry [72]
		Electrostatic sensor [73]
		Inductive sensor [74]
		Capacitively coupled electrodes [75]
		In-situ SEM [76]
		Acoustic emission [77]
Lubrication regime	Film thickness	Ultrasonic sensor [78-80]
		Optical methods [81, 82]
		Capacitive sensor [83]
Wear rate	Wear volume	Electrostatic sensor [84]

Table 5 Off-line sensing technologies relating to Tribo-pairs

Tribo-pair Property	**Physical Feature**	**Sensing Technique**
Surface	Wear debris (concentration, size, morphology and composition)	Ferrography [85]
		Spectroscopy [86]
		SEM/EDX (Scanning Electron Microscopy with Energy Dispersive X-Ray Analysis) [87, 88]
Surface/sub-surface	Topography	Optical 3-D profilometer [89]
		Contact type profilometer [90]
		Microscope [91]
		Atomic Force Microscopy (AFM) [92]
	Tomography	X-Ray Inspections [93]
		Series section method [94]
	Microstructural deformation (Grain-deformation, Phase transformation)	SEM/EDX [95]
		Focused ion beam (FIB) [96]
		Electron backscatter diffraction (EBSD) [97]
	Residual stress	Ring-core method [98]
		Hole-drilling strain-gage method [99]
		Ultrasonic [100]
	Mechanical properties	Hardness mapping [101]
		Nano-indentation [102]
	Work function and surface charge	Scanning Kelvin Probe (SKP) analysis [103]
		Electrostatic sensing [104]
Wear rate	Mass loss	Balance [105]
	Wear volume	3D profilometry [106]

Wear debris sensing is one of the most mature technologies but suffers from the inability to detect low numbers of small particles accurately [24, 25]. The sensor available from Gill [26], for example, is effectively a cumulative system that attracts ferrous particles magnetically and then detects them inductively. There are laboratory scale microfluidic approaches using capacitive methods to detect individual particles that could be embedded [107].

Acoustic techniques become more relevant when sensors are moved closer to the lubricating film as it has been shown that reflections from particles is possible [108]. Arrays of piezoelectric sensors could be used for both listening (allowing time of flight correlation techniques to be used across an array) and for active measurement by using resonance techniques at high ultrasonic frequencies to measure distance. The basis for this has been used in resonant ultrasonic separators [109], but so far has not been demonstrated for oil debris detection. Although progress is being made in online particle detection, there is still a requirement for improvement, and, wear is being detected after a significant amount of it has happened. Once again, to give better resolution of particles, small scale sensors are required and thus it is better to measure within small scale films, rather than in bulk supply pipes. The alternative is to take samples of the oil and determine the debris content, but this runs the risk of the sample not being truly representative of the whole, particularly when there are only a few particles present.

Ultrasonic techniques at small scale have also been investigated for lubricant thickness in the laboratory [110] and later used to investigate the oil film thickness between pistons and cylinders [111], with the conclusion that the techniques offered some promise. Other active techniques for condition monitoring include time of flight measurement for wear of solid surfaces [33]. Historically these have been considered too variable for accurate in situ measurements, but tests have shown that it is possible to measure 10s of microns of wear at high speed (100kHz) with careful signal processing and understanding the operating environment. Similarly, but at a larger scale, in [112], guided ultrasonic wave tomography using an array of transducers was evaluated over a 21 month period to measure wall thickness loss in pipes, again previously considered too variable for practical use. The conclusion here again is that, with care, the spatial diversity of array measurements allows improved measurement stability and in-situ measurements to be taken.

Optical techniques offer a direct approach to surface roughness and potentially offer a better resolution but are also more difficult to integrate [38]. They are commonly used in instruments for measuring surface profiles and can very quickly give the profile of an area. Of more obvious interest for embedded monitoring are optical fibre sensors. Optical fibre sensors offer the potential to be true distributed sensors as the fibre can be responsive at any point along its length. Optical fibre parameters include absorption, transmission, reflection, refraction, and polarisation.

Currently, the measurements and analysis of tribo-pairs are mainly off-line, which requires a physical sample to be taken from the lubrication system and analysed in the laboratory. The first step for in-situ embedded measurements would be the monitoring of surface condition, for which optical fibre sensors offer potential. As an example, a fibre Bragg grating has been integrated close to a bearing surface to successfully measure the temperature [113]. A signal related to mechanical deformation can also be extracted, pointing to an interesting development in that two measurands could be monitored independently from the same sensor, given that they are effectively guaranteed to be separated in frequency.

Another method for monitoring the surface condition and wear mechanisms is the electrostatic sensing technique, which was originally developed for condition monitoring of the gas path of jet engines and turbines [114]. Development studies have also been carried out to utilise this technology to monitor adhesive wear in oil-lubricated contacts. Work to date has shown that when tribological surfaces undergo transition from normal wear to more aggressive end of life wear mechanisms (such as abrasive and adhesive, and/or high levels of wear debris generation) electrostatic sensors can detect these gross changes that happen at quite large-scales [104, 115-125]. However, a single point measurement is not particularly useful as surface changes are likely to be heterogeneous. Therefore, either a wide measurement area or measurement at multiple points will be required. A moving surface partially mitigates this as continuous time data can be obtained for the moving area. If the system is rotating or reciprocating then repeating data for the same measurement point is available, as the same point will rotate beneath the fixed sensors every revolution. Multiple sensors across a width would then allow a rich dataset to be obtained. However, the main hindrance to tribological measurements at small scale is the lack of suitable sensors. At present there are no practical embedded sensors that allow small scale measurements to be taken. Thus, there is a requirement to develop array-based sensors for extracting raw surface condition data.

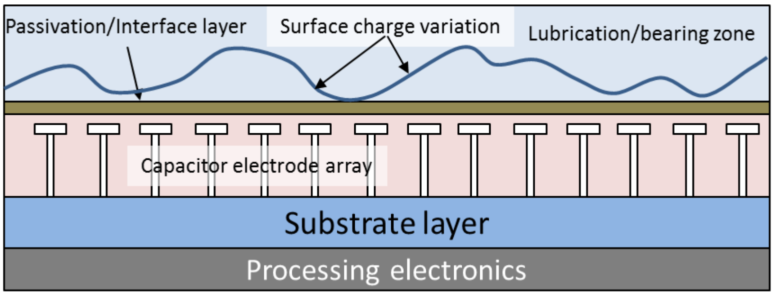

Figure 4 Example of a multi-sensor structure

There is precedent for a smaller charge-based sensor development in the form of fingerprint sensors. These are typically used in the IT world for biometric recognition and identity authentication [126]. An example illustrative structure is shown in Figure 4. Such a structure could in principle be developed as embedded real-time sensors for wear monitoring. An array sensor would be capable of measuring variations of charge across a section of the surface. Surface thickness variation measurement would also be possible, as a repeating change across all elements will be related to this. Thus, multiple surface conditions could be measured using a single sensor system.

For lubricant film thickness measurements, the best approach would be to use a form of non-contact measurement at small scale to evaluate the conditions in or around the lubrication film. The best candidates appear to be electrostatic/capacitance [127, 128], ultrasonic [78] and optical [81]. Acoustic emission techniques can also be revisited for small scale devices close to the wear point, as it may be possible to detect scuffing acoustically at micro-scale, but this has not been investigated yet. On-line oil analysis could provide information about the condition of the surfaces being lubricated, as well as the condition of the lubricant.

3.3. Operating condition

To assess the operating condition (and hence infer machine or component usage), the following have been identified as targets to monitor:

- Load; speed; friction / torque; power consumption; stop-start frequency; transients; change of direction
- Temperature; humidity

Not everything listed above will need measuring as some are related to each other so by measuring one parameter another can be predicted or calculated. Table 6 shows the scope of real-time sensing techniques which can be used to determine the operating conditions. Note that off-line techniques are not applicable here. Compared to tribo-pairs and lubrication status, operating condition monitoring has been largely been achieved with currently available techniques.

Table 6 Sensing technologies relating to Working Conditions

Working Condition	Physical Feature	Sensing Technique

Operating condition	Load	Load cell (force transducer) [129]
		Dead load [130]
	Displacement/ velocity/ acceleration	Optical (displacement) [131]
		Linear variable differential transformer (LVDT) [132]
		Eddy current sensors [133]
		Tachometer [129]
		Laser alignment system [134]
		Electrostatic sensor [135]
		Pulse sensor [48]
		Piezoelectric angular velocity sensor [136]
		Electrodynamic velocity sensor [137]
	Vibration	MEMS [138]
		Piezoelectric accelerometer [48, 139]
	Friction/Torque	Piezoelectric sensor [140, 141]
		Photoelastic sensor [142]
		Strain gauges [48]
	Power consumption	Electromechanical watt-hour meter [143]
		Electronic metering devices [144]
Environment	Humidity	Resistive/capacitive sensor [145]
	Temperature	Thermocouple [146, 147]
		Thermography [148]
		Fibre optics [149]

3.4. Established techniques

Vibration monitoring has been applied successfully for many years to detect more deleterious conditions in operational machinery and its use is widespread [150]. As machines are moving systems, there are always dynamic signals that can be captured, and the technology to capture these signals is well established, robust and usually relatively low-cost and simple to fit. Vibration sensors are widely available in many shapes and forms from displacement to accelerometers measuring single axis or multiple axes. Of relevance here, are silicon MEMS sensors as their integrated manufacture and small size makes them both low cost and reliable. They have found application as airbag sensors in the automotive sector. Vibration sensors can generally be retrofitted to machinery and allow data to be analysed in both time and frequency domains. They have proved successful in many applications particularly for gear, bearing and shaft monitoring. In Aviation, vibration monitoring of helicopter drive trains (HUMS) is mature and established for both military and civil applications [151-153]. In the rail sector, Perpetuum's self-powered vibration condition monitoring system has proved successful at monitoring the axles and the condition of the track – a benefit of multiple sensors making repeated measurements [154].

Acoustic emission has also been used for many years at a macro scale and [155] gives a good overview of available techniques. It also includes results of an experiment using 2 acoustic emission sensors on a slow speed bearing. However, damage related emission signals were only evident after the damage had occurred. This experiment was at a large scale, but similar results have been achieved at a smaller scale [156] (although still not micro) where again emission was only significant as major wear occurred. It was possible to make some conclusions about the nature of the wear process and so there may be potential in smaller scale acoustic emission sensors closer to the wear surface, but this has not been investigated yet.

4. Summary and conclusions

In this paper we have proposed the concept of how machinery condition monitoring can be taken to the next level, through micro-sensing of tribological phenomena occurring between contacting surfaces. The rationale and benefits for doing this are to enable improved operation, management and, ultimately, design of complex and high-value assets. We have discussed how tribological phenomena are key to this goal, as in-situ measurements of tribological phenomena are necessary to provide an early indication of impending failure. By considering wear transitions and wear rates it is possible to distinguish between benign and potentially harmful scenarios and therefore determine with greater accuracy the health of a machine at any point in its life.

For this approach to be successful it is necessary to develop a comprehensive and holistic monitoring strategy. In order to focus areas for future sensing technology development, we have grouped factors influencing the wear process into three key areas: namely lubricant condition, tribo-pair condition and operation condition. Through our comprehensive review of developing and state-of the-art tribo-sensing, we have identified the potential technologies for monitoring or measuring the physical parameters associated with these three groupings.

Reference to the functional requirements for a condition monitoring system, as set out by ISO-13374, shows that once the foundational tribo-sensing systems are in place, then this comprehensive condition information can be used to deliver higher-level functionality, such as Advanced Diagnostics, Prognostics and Advisory Generation. Data Manipulation and State Detection are also important to this. With the development and proliferation of multi-sensor configurations, there is also a need for advanced data fusion strategies for robust decision making [157]. In order to complete the process, a review of Advanced Analytics and Machine Learning applications for Machinery Condition Monitoring is planned as a follow on to this paper.

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