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Tribology as Basis for Machinery Condition Diagnostics and Prognostics

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Abstract: A prognosis of the machinery condition is an important potential tool to avoid unpredictable and expensive disturbances, failure and shut down in industrial production and transportation. A diagnosis of machinery condition can be carried out based on online condition monitoring. The prediction of future performance needs, in addition to knowledge of the present state, also a good understanding of trends and physical laws influencing the progress of the deterioration processes in components. Tribology offers an understanding of the wear and friction related phenomena in machinery and their mechanisms. After a short transient period of running-in wear, the wear process is linear for a long period at steady state running but it is close to exponential at catastrophic wear. Monitoring based regression signal analysis offers a new possibility to predict wear progress and wear failure. The VTT Diagnostic Circle is a method for integrated tribological and vibration analysis of machinery condition.

Keywords: *Tribology, condition monitoring, diagnostics, prognostics*

1. Introduction

In our society, a trend for increasing interest and higher priority to reliability, maintenance, safety and security can be observed. This is mainly fuelled by two trends. On one hand, the technological development has resulted in increased complexity in industrial and transportation machinery, and in production and information systems that makes them more vulnerable for failures and disturbances. On the other hand there is an increased demand in the society for improved control of economy, environmental risks and human safety [1].

Advanced technology offers today many new solutions for improved machinery reliability and availability. The skill to implement these new techniques in products and production systems is today an important industrial competitiveness argument, as was shown in a large national Technology Programme carried out by 25 companies and four research institutes and universities in Finland in1996-2000 [2]. However, the challenge to manage to predict failures and disturbances, and to estimate the remaining lifetime of components, mechanical systems and integrated systems is a very tough one for the

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researchers and engineers. The individual components of a system are subjected to different, often varying loads, and other process and environmental conditions which may affect their performance and deterioration rate [3, 4, 5]. The development of improved diagnostics and methods for predicting failure and lifetime management involves combining condition monitoring with historical data and process data as well as models [1, 6].

In machinery diagnostics we are evaluating the present condition of machinery based on monitored information and earlier experience from the same or similar machines. In prognostics, on the other hand, we are predicting what the condition of the machines will be in the coming months or years. A reliable prediction can be done only if we have a very good and deep understanding of the basic mechanisms involved in component performance and failure. One of the most common reasons to problems and disturbances in machines are the wear and friction related failures, also called the tribological failures.

In this article we present different levels and approaches to machinery condition prediction, the tribological basis for evaluating the component wear progress, a method for monitoring based wear prediction and the VTT Tribo-circle integrating tribology and vibration signal analysis to one holistic method.

2. Machinery Condition Prediction

In machinery condition prediction we can proceed according to different approaches. One is bottom-up and the other top-down. In the bottom-up approach we focus on the individual components of a machine, such as seals, bearings, rotors etc. and perform a separate analysis for each component regarding the loading conditions and the performance and condition of the component. Such an analysis is based on understanding the fundamental physics behind the contact mechanisms, load distributions, stress and strain patters, elastic and plastic material response, surface fracture behaviour, contamination debris interactions and surface chemistry. This is the physics based approach indicated in Figure 1. The physics based approach is suitable to use when we have identified the critical component for a machine, e.g. a certain bearing, and want to estimate its risk for failure and lifetime.

Level	Example		Approach
Machinery	Production line, FMS, paper machine, factory	=>	Statistic
Machine	Car engine, robot, compressor, valve, pump	=>	Hybrid
Component	Gears, bearings, seals, sliders, tools, rollers	=>	Physics based

Fig. 1: Different Approaches to Machinery Condition Prediction are Suitable Depending on the Level of Complexity of the Component or Machine Studied

However, in larger machine systems the situation is often such we do not know which components are the critical ones. Disturbances may seem to occur randomly at different places in the machines. We may also lack good enough methods to estimate failure risks and lifetime for certain components due to shortage in the general understanding of the more detailed failure mechanisms in the components. Then a top-down approach is more suitable. In this we may base the evaluation on documented information of previous failures and their frequency or interviews with experts in charge of the operations to identify their opinion about critical parts, failure root-cause understanding, interactions and sensitiveness. This information can be systematically collected and processed by statistical methods. The top-down method can be used to estimate the overall probability of failure of a certain type of machine or component, or the number of probable failures *e.g.,* during the next week. It can also be used to identify the most critical machines and components. However, it does not usually indicate which specific machine or component from a number of similar components will be the next to fail.

In small machines with limited number of components a combined approach, called hybrid approach in Figure 1, may be the most suitable. This kind of cases would typically be *e.g.,* valves, pumps, engines and similar.

The difference in system level approach and component level approach is illustrated in Figure 2. On component level we follow and monitor one or some certain physical parameters, such as vibration signal or surface temperature that we know are well reflecting the condition of the component. On-line monitoring gives us a possibility to use the information before failure occurs and take actions to influence on the failure event or failure time. In the system level the accumulation of disturbances can be monitored. Failures of critical components cause disturbances in production whereas in the case of some less critical components the component failure does not disturb the production. On the other hand, production disturbances may also be caused by other reasons than component failures, including also e.g. scheduled maintenance stoppages. In combination, monitoring and evaluation of data from both levels, the actions can be planned and scheduled in such a way that the number of unexpected failures and disturbances can be minimised.

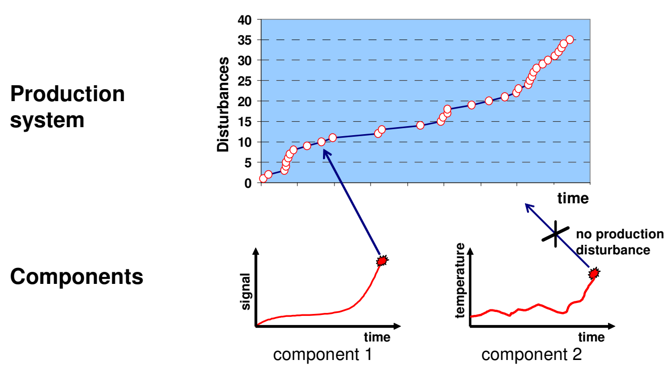


Fig. 2: Trends in the Physical Behaviour and Performance of Single Components are Monitored in the Component Level Approach while the Cumulative Number of Disturbances and Failure Events is Studied and Analysed in the System Level Approach. Figure adapted from [7].

3. Tribology – Controlling Friction and Wear

Tribology is defined as the science and technology of interactive surfaces in relative motion. According to that, tribology focuses on wear, friction and lubrication. In all moving interactive surfaces there is a counterforce created that resists the motion, the frictional force. The interaction results in surface loading and wear. Lubrication is the most efficient way to influence on friction and wear.

Uncontrolled interacting surfaces in machines results in high friction and wear, functional disturbances, failure and break down. A more detailed study of the mechanisms that take place in the process of two interacting surfaces shows that there are mechanical changes on different levels, chemical changes on the surfaces and material transfer, as shown in Figure 3. The mechanical changes are studied on macro level, micro level and even nano level.

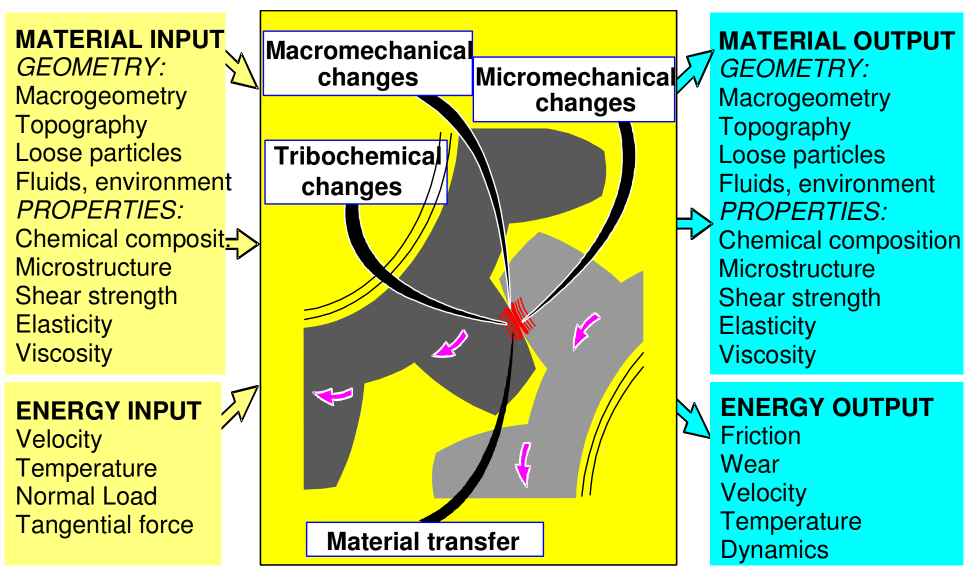


Fig. 3: The Tribological Process in a Contact Between Two Interacting Surfaces in Relative Motion Includes Mechanical and Chemical Changes that Depend on the Input Parameters and Result in Changed Contact Conditions and Changes the Output Parameters After a Certain Time

The tribological process that takes place between the two interacting surfaces is influenced by a set of parameters. Some of them are geometry related such as the macrogeometry, surface topography, loose particles in the contact originating from wear of contamination and dimensions of lubricant films and transfer layers. Some are related to material properties such as chemical composition of bulk materials and surface layers, microstructure, viscosity, elasticity, plasticity and fracture toughness. Some are related to the energy introduced in the interacting contact such as surface velocity, normal load, tangential force and temperature.

With these input parameters the tribological rubbing interaction process takes place between the surfaces and results in changes in some of the parameters such as generation of reaction layers on the surfaces, wear scars, wear products or polishing of surfaces. Some of the changes are energy related such as generated friction, wear, changed velocity and surface temperature and the resulting dynamic behaviour.

The open tribology literature includes a large amount of studies describing these interactions and which parameters are governing the friction and wear behaviour in different applications [8, 9, 10, 11]. When this information is used to support machinery condition prediction it is interesting to find out laws between the interacting parameters and trends in the progress of wear. On the very basic level four different wear mechanisms are defined: adhesive wear, abrasive wear, fatigue wear and tribochemical wear. This classification is surface physics related and explains the mechanism of material response to a moving surface load and how this results in material detachment. However, in practical machinery applications the wear classification is not so easy since several mechanisms are taking place at the same time and their degree of domination may vary during the wear process.

4. Component Wear Progress

When considering machine components it is often fruitful to look at the typical pattern for wear progress at different stages of the wear process. We can roughly identify three characteristic stages, as shown in Figure 4. Stage one is the running-in wear. As new surfaces for the first time are in contact with each other they try to accommodate to each other to easier allow the continuous process of interaction. For rough surfaces polishing takes place. Protective oxide films are rubbed off and the formed naked surface reacts chemically with the environment forming reaction films. Some material flakes from the surface may be rubbed off and attach to the countersurface forming transfer layers. Running-in wear is normally a very short stage. During running-in the wear rate usually decreases as the surface irregularities are gradually removed and the real contact area increases [12].

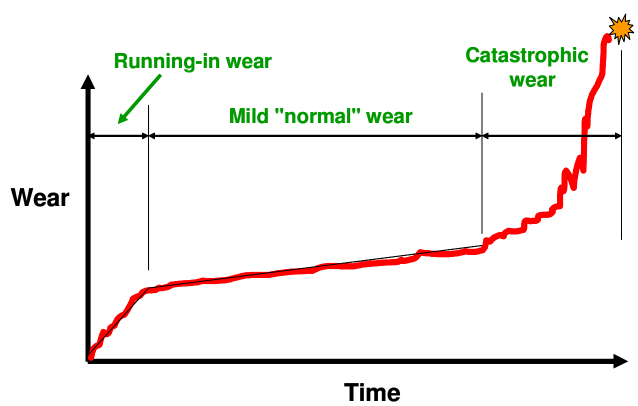


Fig. 4: The Wear Process Proceeds with Three Typical Stages, the Running-in Wear, the Mild or "Normal" Wear and Catastrophic Wear Resulting to Failure

If the running-in process is unsuccessful it may shortly result in a process of increased and accelerated wear and catastrophic failure. On the other hand, if the running-in process proceeds smoothly as planned it results in a second stage with contact conditions where the surfaces are well accommodated to be continuously in sliding contact with each other with low wear and low friction. This is a steady state condition that can be called mild or "normal" wear. Bearings, gears, engine sliders and similar may prevail their function in these conditions for many years. The wear of the surfaces is only on a molecular level and is typically as low as down to 50 nm of wear depth/hour [13, 14, 15]. The wear progress at this stage is typically linear.

Since components are the building blocks of machines and production systems, their performance and deterioration is interrelated with the performance and operation of the machine and with the process conditions. The wear progress depends on the material and surface properties but also on the type of contact and motion of the components as well as on the loading they are subjected to. Mechanical, thermal and chemical loads may act simultaneously or separately, and their magnitude and type may change with time due to progressive wear, accumulated damage or e.g. changes in the machine operation or process conditions or lubrication. The changes in loading conditions may result in a transition of the wear progress, usually an increase in the wear rate [16]. Sometimes an increase in load, speed or temperature may cause a new running-in process such that after a temporary short period of rapid wear the wear rate slows down again and stabilises on a new steady state level. The transition may also be so strong that it induces the third stage of wear progress, with a rapidly accelerated wear rate resulting in catastrophic failure [4, 17]. Onsoyen [4] gives an example of the transition by considering a plain journal bearing. After a stable steady state period of constant wear rate, the clearance of the bearing becomes high enough to change the dynamic behaviour of the shaft, which results in transition to severe wear with an accelerated wear rate. The wear progress in the rapidly accelerated stage becomes exponential.

Under very good lubrication conditions the lubricant carries the load and the surfaces may be separated by the lubricant film such that practically no wear in the form of material loss from the component surfaces takes place. Even under these conditions damage of the surfaces may accumulate with time and the components will suffer from surface fatigue, resulting in the initiation and growth of fatigue cracks giving rise to material loss by flakes loosening from the surface and to transition into rapid wear resulting in catastrophic failure [4, 17, 18].

Onsoyen [4] presented the following simple model for the wear depth as a function of time

$$h(t) = h_o + h' \cdot t \tag{1}$$

where *h(t)* is wear depth, *t* is time, h_o is the contribution from running-in and *h*' is the wear rate, i.e. the increase of wear depth per unit of time. The wear rate *h'* is a function of the selected stressors, i.e. the factors affecting wear. Andersson [3] has applied the same equation for steady state mild wear in sliding contact, expressing the wear rate as

$$h' = k \cdot p \cdot v \tag{2}$$

i.e,. as a function of contact pressure *p*, sliding speed *v* and the wear coefficient *k*. The wear coefficient can be determined experimentally and the model has been used to predict wear in several applications successfully.

Since the rate of wear progress usually changes from mild to severe becoming exponential towards the end of the lifetime, Jantunen [19] has used a simplified numerical time dependent expression for the wear rate referring to his earlier work [20]

$$h'(t) = A \cdot \frac{t_c}{t_c - t} \tag{3}$$

where A is a time independent coefficient and t_c is the lifetime (time to reach a critical wear depth). According to the formula, the wear rate tends to infinity as the end of the lifetime is approached. From this formula Jantunen [19] derived by integration the following equation for the wear depth

$$h(t) = -A \cdot t_c \cdot \ln\left(1 - \frac{t}{t_c}\right) \tag{4}$$

The transitions in the wear progress are complex phenomena and difficult to model. Jantunen's formula is a numerical expression for the wear depth rather than a physical model, but it is an attempt to be able to account for the transition in the wear progress from mild to severe accelerated wear in a simplified way.

5. Monitoring Based Wear Prediction

Wear tests can be made in order to study the wear behaviour of materials and components and the effects of various factors on the wear rate and mechanisms and the transitions in the wear progress. Wear data obtained can be presented in the form of wear maps which may show the areas of different wear mechanisms, contours of constant wear rate, or the transitions from mild to sever wear for a certain material pair as a function of factors influencing wear such as e.g. load and speed [16, 21]. In the case of steady state wear the knowledge of the wear rate under certain operating conditions allows us to predict how long it will take that the component wear reaches a certain predefined value if operated in that range of conditions. This kind of approach can be used to predict the progress of mild wear or, for example, general wear in known abrasive environments. The information and knowledge acquired by testing can be used as basis for developing methods for wear monitoring and predictions.

Selection of suitable monitoring methods requires a good knowledge of the failure mode of components and the results of the failure, i.e. what are the indications of a failure being developing [22]. The most commonly used monitoring methods include vibration and oil analysis. The former can be used for detecting loose fittings, misalignment etc. which may result in wear, and to detect increases in vibration level caused by wear. Acoustic emission (high frequency vibrations above 100 kHz) responds to rapid changes in the surface, e.g. cracks. Oil analysis detects changes in lubricant properties and unexpected presence of contaminants, and the analysis of wear debris in the oil reveals changes in type and severity of wear [23]. Using more than one monitoring method or parameter usually gives more reliable results, and hence vibration and oil analysis are often both used simultaneously for monitoring machines and components [24, 25].

The response of various indirect monitoring methods to wear progress can be studied by laboratory and pilot testing. In this way it is possible to obtain data about the best suited monitoring method and parameters for certain applications and wear modes under selected conditions, giving the necessary basis for succesful measurement based wear prediction. Tool wear monitoring during machining has been an area of intensive research with numerous articles published [26, 27]. Jantunen and Jokinen [28] have reported of a wide cutting test program in which a number of indirect monitoring methods were tested, including vibration, acoustic emission, sound, spindle power and axial force. They analysed the relationship between a number of signal parameters and tool wear by regression analysis using linear, second and third order polynomials and a logarithmic function. They could then rank the different monitoring methods for the tool types tested on the basis of the goodness of fit with the third order polynomial.

Halme [24] has studied the vibration, wear debris and oil analysis for monitoring a ball bearing in a bearing test bench. The test results showed that a bearing failure could be predicted before it occured by all the three methods but the wear debris and oil analysis showed changes earlier than the vibration measurements. The most significant changes in vibration levels were only seen when the damage had developed to a critical level. He concluded that it would be possible to react to changes in the wear process in a reliable, timely manner by combining the methods in an optimal way.

Jantunen has developed the regression analysis further and applied it to prognosis of wear progression both on rolling element bearings and cutting tool wear [19, 29, 30]. As advantages offered by regression analysis He mentions that regression analysis offers the following. It makes it possible to save the history of the measurement parameter with a limited number of terms stored. This reduces the need of storage space, it follows the development of the monitoring parameter and enables also prognosis. The logarithmic function which was based on a the wear progression model, was found problematic to be used in monitoring due to the fact that its use would require a known lifetime or very laborious mathematics. The third order polynomial which was found to be very promising for tool wear prediction in the earlier studies [28], was too insensitive to the changes in the measurement data after a long measurement period. Hence the third order polynomial has been replaced by a higher order polynomial regression function having a limited number of terms and emphasising the current data. Jantunen [19] has compared the new function with the third order regression and also with linear regression based on the last three measurements as given in standards and obtained a much better fit with the current data when using the new function. He concludes that this regression function seems to work very well with a simulated exponentially developing wear, and he shows that with this function it is possible to predict the behaviour of the signal to a time step of 3% in the future, see Figure 5.

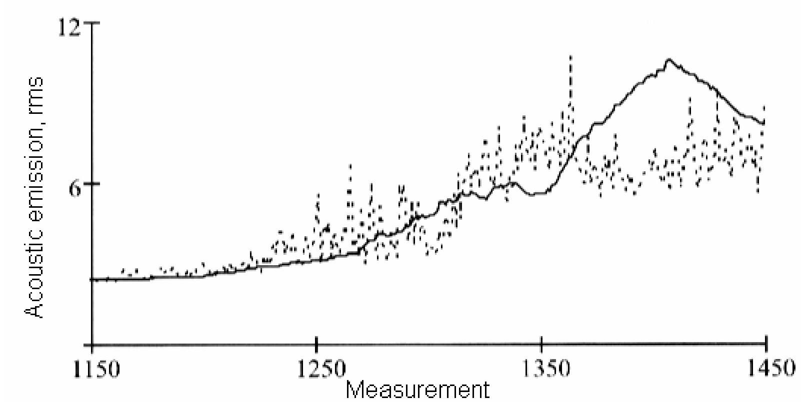
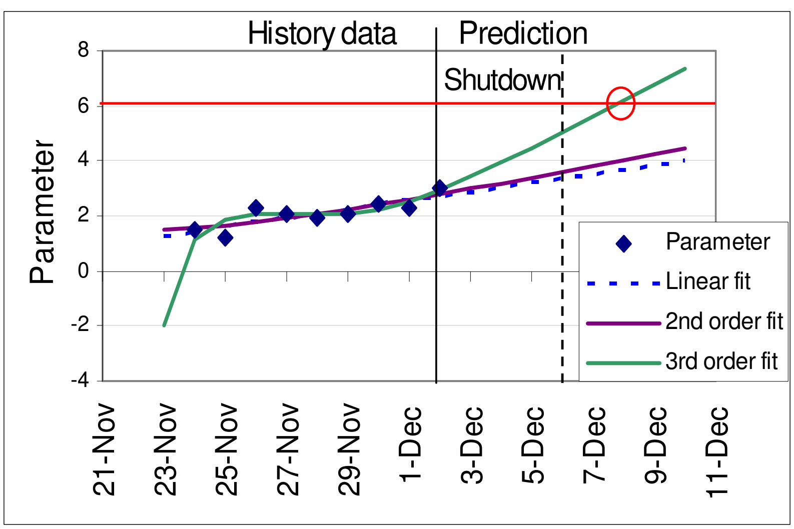


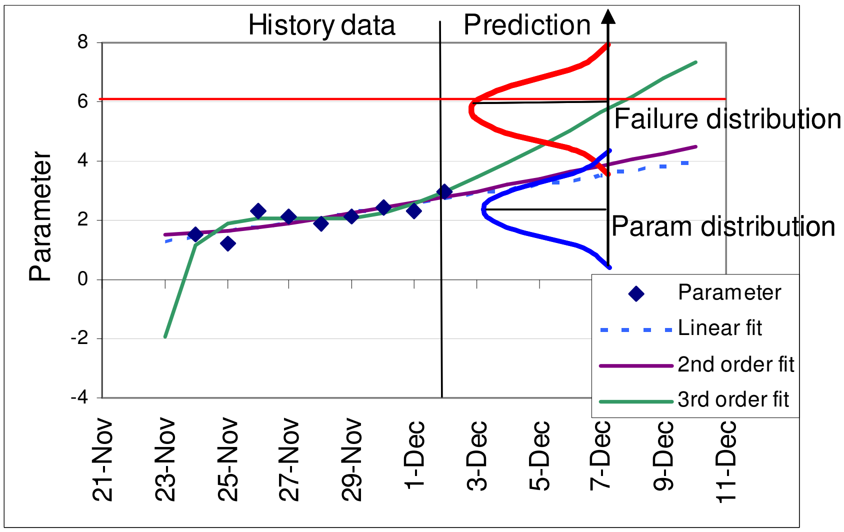
Fig. 5: Prognosis (Solid Line) Corresponding to a Time 3% in Future, Based on Measured Acoustic Emission rms-values (Dotted Line). This Means that e.g. the Prognosis for Measurement Point 1450 is Done Based on Measurement Data from 0 to 1407 [30]

Figure 6 illustrates how the wear progress can be predicted on the basis of monitoring measurements [1]. The vertical axes represent the parameter or a combination of parameters being monitored and the horizontal axes the time. The vertical line indicates the present time, and the parameters obtained from the available data, i.e. the measurements, are shown on the left. They form the history of the current monitoring task. If the wear mechanism is known and models for its progression are available, the future behaviour of the parameter, and ideally a response of the process state, can be estimated by combining the models and the existing data in simulations. The model may correspond to a linear or higher order polynomial equation as in the model suggested by Jantunen [19] for wear prognosis, and the predicted behaviour is obtained from the derived models by polynomial fitting.

Different scenarios can be included in the prognosis by examining also the effects from e.g. possible changes in failure mode or operating conditions on the output of the simulation, i.e. incorporating the wear transitions into the models by some factors. In the figure the different scenarios are represented by the different polynomial fittings. The remaining lifetime or time to failure is given as the time between the present time and the moment where the curve representing the predicted behaviour crosses the horizontal line representing the highest allowable wear limit, see Figure 6a. The worst scenario gives the shortest residual life. Comparison of the values corresponding to the time of the next scheduled shutdown shows whether the machine can or cannot be run until the next shutdown without failure. Including statistical data and distributions in the models allows a more probabilistic approach which also takes into account the stochastic nature of wear progress, see Figure 6b. It allows predictions about the dependability of the machine expressed e.g. as the failure probability at a certain point in time. Since wear and the performance of components is influenced by a multitude of factors, including loading, temperature and other operational conditions as well as any maintenance actions carried out, the conditions and assumptions for which the prognosis is valid should also be given.



a)



b)

Fig. 6: Examples for Prognosis
a) The Different Scenarios are Represented by the Different Polynomial Fittings and Different Wear Models. b) The Stochastic Nature of Wear has been Taken into Account by Parameter and Lifetime Distributions [1]

6. Tribo-diagnostic Circle

Today condition monitoring of critical, failing or ageing machinery components such as e.g. bearings, seals, transmissions, is a normal maintenance task, often including some more advanced signal analysis techniques as well. However, monitoring and signal analysis is seldom accompanied with a detailed tribological wear, friction and lubrication analysis. Nevertheless, the basic problem studied - the changes in performance of moving component surfaces - is just the same. Thus, an integrated approach will offer the best possibilities for advanced and reliable diagnosis and predictions. The VTT Tribo-Diagnostic Circle represents one such approach and is shown in Figure 7.

The starting point for the VTT Tribo-Diagnostic analysis is to define the contact mode (1 in Figure 7 and Table 1) on the identified critical component to be studied. This includes identification of the contact conditions (sliding, rolling, oscillating, etc.) and the lubrication conditions (boundary, hydrodynamic, etc.) in the component. It also includes determination of the specific geometry (radius, surface roughness etc.) and the material properties and structures (hardness, fracture toughness, coatings etc.). The dynamic signals from the contact point are transferred to the signal monitoring device, the sensor (4), through a transfer media (2) that can be a solid material, a liquid or even gas, and this may also affect the signal. For the sensors there is a large range of different units all depending on what particular phenomenon and signal we want to monitor. They may be typically accelerometers, proximity probes, acoustic emission sensors, strain gauges, etc.

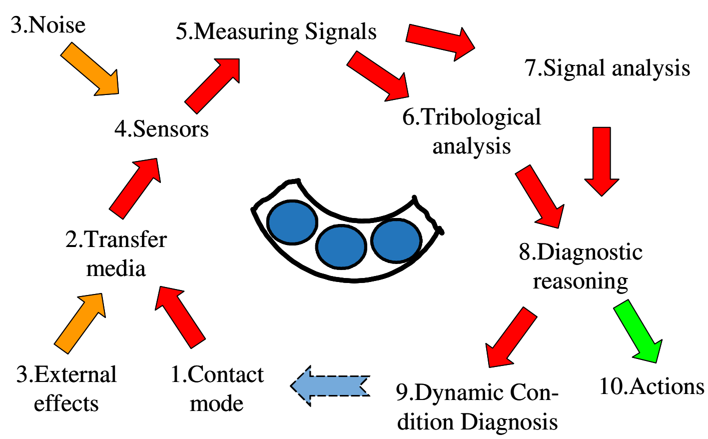


Fig. 7: The VTT Tribo-Diagnostic Circle Shows the Components and Path to Proceed from Contact Analysis over Monitoring, Signal Analysis and Diagnostics to Prognostics and Maintenance Decisions

But life is not this simple. The sensor does not only detect the signal coming from the specific contact spot that we are interested in but it also receives signals from other contacts and sources both inside and outside the machinery (3). Using a set of measuring signals (5), component data (temperature, pressure, acceleration, strain etc), signal analysis data (frequency, direction, amplitude, time delay etc) or tribological data (friction force, wear, contamination etc) is transferred to tribological (6) and signal analyses (7).

The measured signals are used on one hand for signal analysis of dynamic motions by methods such as spectral analysis, kurtosis method, signal averaging etc (5). The same or other measurements and signals are used for the tribological analysis (6). It consists of stress and deformation analysis, surface chemistry analysis, friction energy analysis, fluid chemistry analysis, fluid flow analysis, debris generation analysis and surface deterioration analysis.

The signal analysis and the tribological analysis give the information needed for the diagnostic reasoning (8) that can be human logical reasoning e.g. by comparing surface failure patterns to existing failure maps, it can be statistical analysis and reasoning by computers and it can be automatic reasoning by advanced software packages including typically pattern recognition, fuzzy logic, expert systems and hybrid structures.

The result of the diagnostic reasoning is a diagnosis of the dynamic condition (9) in the component contact where the changes in the condition mode (stable, instable, slowly decreasing/increasing, chaotic, emergency) is defined, the basic tribological failure mode (adhesive, abrasive, fatigue, tribochemical wear and increased/decreased/seizure by friction) is defined and further the appearance based tribological failure mode (pitting, scuffing, fretting, scoring, cavitation etc) is defined. This information combined with theoretical and historical knowledge of the same or similar components and their failures is the main input used for a prediction of the probability for failure and the probable remaining time to failure, that is, for an advanced prognosis.

The actions (10) recommended to be taken based on this process could be e.g. component replacement, repair, redesign, installing on-line monitoring and warnings or simply shut down and recirculation of the device.

This process is illustrated in Figure 7 as a circle symbolising the on-going activity in diagnosis. The contact conditions described and analyzed will, eventually, result in changes in the contact mode (e.g. smoothening of surfaces, wear, deformations etc) and in changes in the signals that are again analyzed and result in a new diagnosis and new actions to be taken. The integrated diagnosis of the machinery condition gives the best basis for calculating trends and predicting future condition and lifetime.

7. Conclusions

In machinery condition prediction we can proceed according to different approaches. The system level approach is based on statistical analysis of accumulated data on disturbances and failures whereas the component level approach is physics based focusing on individual critical machine components and monitoring physical parameters reflecting their condition. The VTT Tribo-Diagnostic Circle is one approach towards more accurate diagnostics and prognostics by integrating tribological knowledge into monitoring and diagnostic techniques. It describes the process of on-going activity in diagnosis from contact mode analysis over monitoring, signal analysis and diagnostics to prognostics and maintenance decisions.

Tribology offers an understanding of the wear and friction related phenomena in machinery and their mechanisms. The wear progress depends on the material and surface properties but also on the type of contact and motion of the components as well as on the loading they are subjected to. In the wear progress in machine components three stages can often be identified, a short transient period of running-in wear, a longer linear steady state period of mild wear and finally catastrophic wear which is close to exponential. The wear rate can be modeled as a function of the factors affecting wear and simple models with an experimentally determined wear coefficient have been used to predict wear in several applications succesfully in the mild wear regime. However, the operating conditions vary and dynamic changes may cause transitions in the wear progress leading to the third stage of wear progress, with a rapidly accelerated wear rate resulting in catastrophic failure.

Measurement based wear predicition requires good knowledge of the failure mode and its indications such that suitable monitoring methods and parameters can be selected which react to the indications of the wear progress and its transitions. If the wear mechanism is known and models for its progression are available, the future behaviour of the parameter can be estimated by combining the models and the existing measurement data. Different scenarios can be included in the prognosis incorporating wear transitions into the models. Regression models have several advantages including the reduced need of storage space for the measurement data and the ability for prognosis. A higher order polynomial regression model is sensitive for the changes in the measurement signal and thus it also reacts to the transitions in wear progress. The stochastic nature of wear progress can be accounted for if statistical data and distributions are included in the models to allow a more probabilistic approach.

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Appendix A

Table A1: Components in the VTT Tribo-Diagnostic Circle

1. Contact Modes
Components
- Sliding bearing
- Rolling contact bearing
- Gear contacts
- Cutting tools
- Forming tools
- Erosion resistant components
- Abrasion resistant components
- Seal
- Lubricant (oil, water, air)

Contact conditions
- Sliding (two/three body)
- Impact (solid body, particles & fluids)
- Rolling (fatigue)
- Oscillating (fretting)
- Chemical dissolution

Lubrication mechanisms
- Hydrodynamic lubrication
- Elastohydrodynamic lubrication
- Mixed lubrication
- Boundary lubrication

2. Transfer Media
Solid
- steel
- polymer
- cast iron

Liquid
- oil
- water
- solution

Gas
- dry and humid air
- gas

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3. Noise/External effects
Vibrations
Temperature
Contaminations
Pressure

4. Sensors
Accelerometer
Proximity probe
AE sensor
Strain gauge
Thermometer
Pressure sensor
Optical sensor
Surface wave sensor

5. Signals
Component data
- Force
- Pressure
- Deformation
- Stress
- Movement
- Acceleration
- Temperature
- Sound

Signal Analysis Data
- Frequency
- Direction
- Amplitude
- Time delay

Tribological Data
- Friction coefficient
- Surface wear
- Wear products
- Lubricant films
- Surface films

6. Tribological analysis
Stress and deformation analysis
Surface chemistry analysis
Friction energy analysis
Fluid chemistry analysis
Fluid flow analysis
Debris generation analysis
Surface deterioration analysis

7. Signal analysis
Spectral analysis
Discrete frequency monitoring
Shock pulse monitoring
Kurtosis method
Cepstrum analysis
Signal averaging
Wavelet analysis
Envelope analysis
Neural analysis
Statistical analysis
Fuzzy analysis
Dynamic signal feature modelling
Simulation analysis

8. Diagnostic Reasoning
Logic
Statistical
Automatic
Intelligent

9. Dynamic Condition Diagnosis
Condition modes
- Stabile
- Instable
- Slowly controlled decreasing
- Fast controlled decreasing
- Chaotic
- Emergency

Tribological failure - basic
- Adhesive wear
- Abrasive wear
- Fatigue wear
- Tribochemical wear
- Seizure by friction
- Increased friction
- Decreased friction

Tribological failure - appearance
- Pitting
- Scuffing
- Spalling
- Fretting
- Scoring
- Galling
- Gouging
- Cavitation
- Diffusive wear
- Electrical wear
- Impact wear
- Solution wear
- Mild wear
- Severe wear

Reliability
- Life time
- Probability of failure

10. Actions
Component replacement
- Component change
- Oil change

Repair
- New adjustments
- New coatings

Redesign
On-line monitoring and warnings
Shut down and destroy

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