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**INTEGRATED PROJECT:**

**Dynamic Decisions in Maintenance**

**DYNAMITE**

Project No IP 017 498

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**Prognostics for Industrial Machinery Availability**

IC1 Conference Paper

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Abstract
In our society, a trend for increasing interest in and higher priority given to reliability, maintenance, safety and security can be observed. The technical development offers every day new and more advanced tools to achieve this. 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 difficult one. On this route we are today only taking the first steps. For the next steps, deepening of our knowledge in many of the technological areas involved is needed, and in addition it is necessary to find holistic approaches and methodologies to integrate the different techniques involved. In this article we will present a method to integrate the tribological knowledge into monitoring and diagnostics techniques, show how the step from diagnostics to prognostics can be taken, outline a new European concept for IT-based maintenance and show the benefit of networked global diagnostic centres.

Keywords: prognostics, condition monitoring, diagnostics, maintenance, reliability

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 [Holmberg et al. 2004].

The technical development offers every day new and more advanced tools to achieve this. We get an improved understanding of causes to failures and system disturbances, better monitoring and signal analysis methods, improved materials, design and production techniques. The development is especially rapid in the information technology (IT) related areas. The size of sensors has decreased to micrometer level in Micro Electro Mechanical Systems (MEMS) sensors, and at the same time their performance is improved and their prize has dropped by orders of magnitude when produced in large series [Paula, 1997; Yao, 2000; Judy, 2001; Halme, 2002; Jantunen, 2002; Hierold, 2004]. Wireless communication can be used effectively over both global and local distances and to single or multisensor systems [Akyildiz et al., 2002, 2005; Halme, 2003; Gonzalez-Castano, 2005; Myers; 2005; Vidqvist & Halme, 2005]. Software development such as artificial intelligence, expert systems, fuzzy logic, pattern recognition and hybrid systems makes it possible to process larger volumes of

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 entitled *Competitive Reliability* and carried out by 25 companies and four research institutes and universities in Finland 1996-2000 [Holmberg, 2001]. 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 researchers and engineers. On this route we are today only taking the first steps. For the next steps, deepening of our knowledge in many of the technological areas involved is needed, and in addition it is necessary to find holistic approaches and methodologies to integrate the different techniques involved.

In this article we will present a method to integrate the tribological knowledge into monitoring and diagnostics techniques, show how the step from diagnostics to prognostics can be taken, outline a new European concept for IT-based maintenance and show the benefit of networked global diagnostic centres.

2. The VTT 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 analysis, that is a 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 2.1.

The starting point for the VTT Tribo-Diagnostic analysis is to define the contact mode (1 in Figure 2.1 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 lubrication) 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, 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.
Figure 2.1 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 2.1 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.

3. From Diagnostics to Prognostics

The capability of machinery or a production line to sustain its ability to perform its required function without failure until the next scheduled shutdown is directly influenced by the state and remaining lifetime of its critical components. The graph in Figure 3.1 gives a schematic presentation of the deterioration of a component or machine with time. Deterioration can be observed from different time perspectives: in design stage for new machinery we need to use models, by monitoring the machine during use we obtain information about its current state, and using historical data means looking back, i.e. using information about deterioration that has already taken place. When historical data is available, either from the machine itself or from similar machines under similar operating conditions, this data can be used both for creating new models, and for improving and verifying existing ones. The aim of diagnostics is to detect faults or failures and to determine the type, location and severity of them, based on analysis of the existing data, including the data obtained by monitoring as well as design data and historical data and even user knowledge. Tribological knowledge is of major importance in understanding many failure mechanisms and their symptoms [Roylance, 2002]. The more knowledge we have about the machines, their operating conditions, possible faults and failure modes and their symptoms, the more accurate and reliable diagnoses are possible. Utilization of the tribo-diagnostic analysis described above provides one possible approach towards more accurate diagnostics.

Whereas diagnostics is focused on the present state of the component or machine, prognostics means looking forward into the future, focusing on the future performance or development of faults in the machine. The most challenging area is illustrated in Figure 3.1 by the area between the vertical lines. In addition to a diagnosis of the current state of the machine and information about its history, prognostics requires models of the progression of the deterioration process, in order to be able to make an estimate of the remaining useful lifetime or the state of the machine at a certain future point in time. Besides mechanical failure, the criteria for failure may also include disturbances or losses in fulfilling the quantitative or qualitative production requirements. Some general guidelines for diagnostics and prognostics can also be found from ISO standards [ISO 13381-1, ISO 17359].
Figure 3.1. Schematic presentation of the deterioration of a machine or component with time. Combining models with monitoring and historical data, forms the basis for giving a prognosis concerning faults, remaining lifetime or the future state of a machine.

In many cases condition monitoring is based on a selected single measurement technique and/or only a few signal parameters, vibration measurements being one of the most common methods. However, process control and automation systems have typically a lot of measurement information as well, and performance data which could also be utilized for diagnostics and prognostics of the machine condition together with the condition monitoring measurements [Cowan & Winer, 2001; Parikka et al., 2001; Jantunen 2002]. The rapid development in sensor technology, signal processing, ICT and other technologies related to condition monitoring and diagnostics as mentioned in the introduction, increases the possibilities to utilize data from multiple origin and sources, and of different type.

Figure 3.2 gives a general schematic diagram of diagnostics and prognostics based on multi-sensor measurements and multi-source data, showing various possible data sources as well as what kind of knowledge or methods can be used. Combining and analyzing condition monitoring data, process data and maintenance data, including results of various inspection duties, forms the basis for the diagnosis and subsequent prognosis which then provides the information needed for maintenance management, decisions and actions. The documentation of maintenance actions, faults and their causes builds up to the existing historical data, and the cumulative data can then be utilized in later diagnostics and prognostics. Condition monitoring, diagnostics and prognostics together with the maintenance management decisions and actions form a continuous process, with new possibilities arising with advances in related technologies and with changes in costs and process.
Condition monitoring
Identification of critical machinery and components
Data acquisition
(on-line / off-line)
Vibration, AE, noise,
p, T, F, pH...
Oil analysis / wear debris
Signal processing and analysis
(Statistical parameters,
FFT, Wavelet, etc.)
Diagnostics & Prognostics
Data fusion, analysis, reasoning,
Models, expert knowledge, trends, thresholding, fuzzy logic, neural nets, ...
Diagnostics & Prognostics
Decision
Maintenance Management
Decision
Maintenance Management
Maintenance and Inspection
Visual inspection,
NDE
Process control
Operational data,
process condition and disturbances
Service and repair data, Failure analysis, Historical data
Identification of critical machinery and components
Knowledge on production process, machinery, structure, loading, service and operational history,
costs, analysis methods (FMECA, FTA, ...)

Figure 3.2. Schematic presentation of machine diagnostics and prognostics based on multi-sensor measurements and multi-source data.

VTT Technical Research Centre of Finland, three technical universities and several companies in Finland are currently developing methods and techniques needed in the different stages of the prognostic process in a three-year project titled Prognos - Prognostics for Industrial Machinery Availability. The research covers areas from the development of new monitoring techniques to tools for supporting maintenance management. The aim is to generate methods for improving and maintaining industrial machinery availability by the development of techniques which enable prognosis of the operational condition, failure probability, and remaining operating lifetime of the machinery and production lines [Helle, 2005].

Figure 3.3 illustrates the development of prognostic methods by showing examples for prognosis based on same measurement data but with different objectives. The vertical axes in the figure represent the parameter or a combination of parameters being monitored and the horizontal axis is time. The vertical line indicates the present time, and the parameters obtained from the available data, e.g. measurements, are shown on the left, forming the history of the current monitoring task. If the deterioration or failure 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. 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. In the simplest case the model corresponds to a linear or higher order polynomial equation and the predicted behaviour is obtained from the derived models by polynomial fitting. The model for wear prognosis suggested by Jantunen [2003] is an example of a higher order polynomial model with emphasis on the most recent measurement data.

Comparison of the predicted future values of the monitored parameter or parameter combination to the values corresponding to the end point or some lower threshold values indicating e.g. alert situation gives information about the operating condition of the machine. 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 threshold limit, see Figure 3.3. 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, and predictions about the dependability of the machine expressed e.g. as the failure probability at a certain point in time can be obtained, see Figure 3.3. Since the performance of machines 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 with it.

![Figure 3.3](image)

**Figure 3.3.** Examples for prognosis based on same measurement data with different objectives of the forecast. The objective may be to estimate the time for failure or the condition or state of the machine at a certain time in future (left), or the dependability of the machine at a certain time in future (right).

4. A European Future Vision for IT-Based Maintenance
The technology development offers a lot of possibilities to develop maintenance and improve safety and reliability - with some of the most advanced approaches looking more like science fiction. But it is relevant to ask what is realistic, what is affordable and what is reliable when talking about future maintenance systems?

One vision of the future is offered in the form of a new Integrated Project of the European Community 6th Framework Programme. The project is called DYNAMITE - Dynamic Decisions in Maintenance. The DYNAMITE project is running over the years 2005-09 and is coordinated by VTT Technical Research Centre of Finland. It includes six research institutes in the UK, France, Spain, Sweden and Finland, two car manufacturers FIAT and Volvo, the machine tool manufacturer Goratu, the automation and maintenance system provider Zenon, and seven SME’s representing related business areas.

The DYNAMITE vision of the future is illustrated in Figure 4.1. Today about 30% of all the maintenance activities in industrial and transportation systems in Europe are unplanned (Komonen, 2005). Actions are taken when failures or disturbances appear. The planned and scheduled maintenance is used as maintenance strategy very commonly, in about 55%. The inspection, service and component replacement is then carried out according to a predetermined schedule, regardless of the component condition and the necessity of the action. This results in unnecessary action costs and, even worse, in service actions like disassembly that may have negative effects on the performance and lifetime of components due to changed aligning, sealing, run-in compatibility etc. Advanced companies have moved, or are today changing their maintenance strategy, to condition based maintenance. This part represents
less than 15 % of the enterprises in Europe. In more developed equipment, sensors have been installed in critical places and devices in the machinery to continuously monitor the condition and to take service actions only when these are really needed.

**Figure 4.1.** The European DYNAMITE concept for future IT-based maintenance.

The DYNAMITE vision takes the maintenance even one step further, essentially taking full advantage of the advanced information technology both related to hardware, software and information content. The measured machinery condition data is picked up with micro size MEMS sensors especially designed for maintenance purpose and low-cost on-line lubrication sensors analysing both the condition of the oil and its contamination. The data is wirelessly transferred to smart tags on components and devices where their identity, history, health and service data is stored. The sensors and smart tags have the ability to communicate with each other and also with PDA’s (Personal Data Assistant) that the maintenance personnel carry with them when moving around in the plants.

The PDA is wirelessly communicating with remote diagnostic centres for more in-depth condition analysis and integration of monitored data with models and history data. The PDA is further communicating with the company’s economic and business systems and providing them with on-line status information about the asset condition and the present risk level as well as scenarios for different options of actions. To manage to maintain this flow of information two requirements must be fulfilled. One is that the total information flow on all levels is structured according to a common e-maintenance semantic terminology and frame. The other is that the company maintenance, economics and business systems are harmonised to communicate with each other and to produce the essential key figures needed for both strategic and day-to-day business decisions.
5. VTT Diagnostic Centre

It is clear that a future IT-based maintenance system will include a very large volume of data, information and knowledge originating from on-line measurement, history data and information and models including interactions of dynamic effects. Some of the more simple processing should be decentralised to a level as low as possible, e.g. to the sensor level. The lower level processing would typically screen out irrelevant data, do sensor validation and transfer emergency warnings based on validated out-of-range signals. On the other hand, we are still left with a large volume of relevant and validated data that needs advanced processing, modelling, statistical analysis, scenario and option generation and human expert team evaluation.

VTT Diagnostic Centre, schematically presented in Figure 5.1, is an example of a recently established site for carrying out the above mentioned functions, especially with regard to machinery diagnostics. The VTT Diagnostic Centre has the equipment and competence to carry out data collection and data refining, to draw conclusions, to make predictions and to give recommendations for actions, at the first stage, based on tribological knowledge and dynamic machinery condition monitoring and analysis.

![Figure 5.1. VTT Diagnostic Centre for remote machinery diagnostics and prognostics.](image)

The VTT Diagnostic Centre has links to VTT machinery diagnostic laboratory devices and offers possibility to tailored remote on-line diagnostics of devices in production sites. The links between the Centre and production cites can be built up according to optional tailored structures such as direct links to devices, links to company local service centres, links to global expert centres or links to plant maintenance organisations as shown in Figure 5.2.
The VTT Diagnostic Centre is one of the founding members of the International Network for Industrial Diagnostics (INID) founded in 2004. The other members are Manchester and Sunderland Universities in the UK, Université Henry Poincaré in France, Växjö University in Sweden and the research centre Tekniker in Spain. INID is a new and effective way to utilise geographically distributed high level technical and scientific knowledge, large technological experience and huge data volumes for innovative solutions and rapid industrial implementation. INID brings together the partners competence, skills and experience through networked and interactive continuous co-operation and it aims at developing new cutting edge technologies, novel scientific concepts and innovative industrial solutions.

6. Conclusions
The VTT Tribo-Diagnostic Circle is proposed as one possible approach towards more accurate diagnostics 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. Whereas diagnostics is focused on the present state of the component or machine, prognostics means looking forward into the future. In addition to a diagnosis of the current state of the machine and information about its history, prognostics requires models of the progression of the deterioration process, in order to be able to make an estimate of the remaining useful lifetime or the state of the machine at a certain future point in time or whether it can be run until the next shutdown without failure. A European future vision for IT-based maintenance, DYNAMITE, will take full advantage of the advanced information technology both related to hardware, software and information content utilizing MEMS sensors and low-cost on-line lubrication sensors together with wireless data transfer and communication between the sensors, smart tags on components and devices where their identity, history, health and service data is stored, and PDA’s (Personal Data Assistant) that the maintenance personnel carry with them when moving around in the plants. Remote machine diagnostics through an international network offers a new and effective way to utilize geographically distributed high level technical and scientific knowledge, large technological experience and huge data volumes for innovative solutions and rapid industrial implementation.
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References


Appendix I

Table 1. 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

3. Noise/External effects
   Vibrations
   Temperature
   Contaminations
   Pressure

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

5. Measuring signals
   - Temperature
   - Pressure
   - Strain
   - Force
   - Acceleration
   - Velocity
   - Distance
   - Dimensions
   - Sound

6. Tribological analysis
   Wear and friction 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

9. Dynamic Condition Diagnosis
   Condition modes
   - Stable
   - 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

10. Actions
    Component replacement
    - Component change
    - Oil change
    Repair
    - New adjustments
    - New coatings
    Redesign
    On-line monitoring and warnings
    Shut down and destroy

Tribological failure - appearance
   - Fitting
   - 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