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SMART bearings: From sensing to actuation

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Abstract- A Centre has been created within Lulea University of Technology (LTU), with support from SKF, to examine the opportunities presented by developments in sensing and communication technologies in adding sensing and analysis functionality to rolling element bearings. One of the goals is the development of an artefact which closes the loop from sensing to actuation and taking advantage of all existing IT, mechanical and maintenance technologies.

I. Introduction

Bearings are among the most important components in the vast majority of machines and exacting demands are made upon their carrying capacity and reliability. Therefore it is quite natural that rolling bearings should have come to play such a prominent part and that over the years they have been the subject of extensive research. Indeed rolling bearing technology has developed into a particular branch of science. SKF has been well to the forefront right from the start and has long led this field.

Among the benefits resulting from the research performed in LTU and supported by SKF is that ability to reduce the risk of premature or in-service bearing failure. By sensing the operating environment in which the bearing functions, the risk of a future failure developing can be identified, and used a basis for planning of maintenance and other interventions. Moreover, by using this knowledge to trigger actions to eliminate damaging operating conditions, future failures may be avoided

Unfortunately, the rolling bearing cannot rotate for ever. Unless operating conditions are ideal and the fatigue load limit is not reached, sooner or later material fatigue will occur. The period until the first sign of fatigue appears is a function of the number of revolutions performed by the bearing and the magnitude of the load. Fatigue is the result of shear stresses cyclically appearing immediately below the load carrying surface. After a time these stresses cause cracks which gradually extend up to the surface. As the rolling elements pass over the cracks fragments of material break away and this is known as flaking or spalling. The flaking progressively increases in extent and eventually makes the bearing unserviceable. The life of a rolling bearing is defined as the number of revolutions the bearing can perform before incipient flaking occurs. This does not mean to say that the bearing cannot be used after then. Flaking is a relatively long, drawn-out process and makes its presence known by increasing noise and vibration levels in the bearing. Therefore, as a rule, there is plenty of time to prepare for a change of bearing.

However, it sometimes happens that a bearing does not attain its calculated rating life. There may be many reasons for this ; heavier load than has been anticipated, inadequate or unsuitable lubrication, careless handling, ineffective sealing, or fits that are too tight, with resultant insufficient internal bearing clearance, and other unexpected physical environment . Each of these factors produces its own particular type of damage and leaves its own special imprint on the bearing. Consequently, by examining a damaged bearing, it is possible, in the majority of cases, to form an opinion on the cause of the damage and to take the requisite action to prevent a recurrence. Actually, these anomalies are the ones the users should take care of due to the risk of fast degradation and catastrophic consequences.

II. Risk assessment for maintenance actions

It has been considered that if a rolling bearing in service is properly lubricated, properly aligned, kept free of abrasives, moisture, and corrosive reagents, and properly loaded, then all causes of damage are eliminated save one, material fatigue. Historically, rolling bearing theory postulated that no rotating bearing can give unlimited service, because of the probability of fatigue of the surfaces in rolling contact. The stresses repeatedly acting on these surfaces can be extremely high as compared to other stresses acting on engineering structures. In the latter situation, some steels appear to have an endurance limit. This endurance limit is a level of cyclically applied, reversing stress, which, if not exceeded, the structure will accommodate without fatigue failure. The endurance limit for structural fatigue has been established by rotating beam and/or torsional testing of simple bars for various materials. That is why inadequate lubrication, improper maintenance, dirtiness etc. constitute the real risks for life reduction. In fact life due to steel fatigue is much longer than most of the machines where the bearings are mounted in. So, one could think that the Remaining Useful Life of the bearing is much longer from physical rather than functional point of view. Therefore risk assessment becomes necessary to mitigate the effects of these undesired elements that reduce dramatically the life of the bearing in case they occur.

A. SMARTness in bearings

Risk assessments have been the real basis for risk based maintenance approach. Actually, the “S” for Safety in RAMS terminology has been a powerful driver to transfer technology from risks for people to risk for machinery. Isaac Asimov, the famous author of Science Fiction books created the three laws of robotic (Asimov, 1942):

a. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
b. A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.
c. A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws.

Reading these statements carefully, one can notice that Asimov already prioritized the behaviour of the machines and created the basis for risk assessment. In summary, risk assessment should be primarily performed to protect human integrity, whether maintainers or operators working closely together with productive assets. However, once the requirements to protect humans are fulfilled, the asset must protect itself. This is a real novelty which pinpoints the concept of SMART devices as protection for people and self-protection of the machinery.

This novelty is not hundred per cent new for SKF rolling elements. One could say that SKF developed the first SMART bearing long time ago when the company started the commercialization of the self-alignment bearing. It has two rows of balls and a common sphered raceway in the outer ring. The bearings are consequently self-aligning and insensitive to shaft deflections and angular misalignment of the shaft relative to the housing. Additionally, self-aligning ball bearings generate less friction than any other type of rolling bearing, which enables them to run cooler even at high speeds. In summary self-alignment bearing is able to modify its behaviour according to malfunctions in the machine correcting these anomalies without human intervention and reducing dramatically the number of shutdowns. This Smartness about misalignment is the greatest advance in self-maintenance of rolling elements. Nowadays SMART bearing project tries to generalize this concept of smartness taking advantage of the existing technologies

Figure 1. Self alignment bearing

SMART bearings must perform evaluation of operational risks as an aid in maintenance decisions concerning assets in certain conditions. These devices will always prioritize the safety of humans but also their integrity when the operating condition modifies the scenario and therefore the risk for the machine is dynamic.

The risk assessment will condition the real maintenance planning for the bearing according to the risks the humans want to accept for them, and for the health of the machinery. Risk tolerance is up to the individual to accept in function of economic, social or environmental conditions. For example, in vehicle health monitoring, most of direct interventions (not taking shop repairs into account), consists mainly of corrective actions aimed at replacing or repairing failing components or components in the course of degradation, of scheduled, generally periodic inspections and of preventive actions such as replacement of equipment items having limited useful life. These actions must be initiated by schedule or degradation process but in both cases, the end user and maintainer are not sure about the real need for the action. The risk assessment will provide the necessary advice to the involved people about the consequences of extending the scheduled replacement or permitting the component to be degraded beyond the established threshold. These consequences will have risk implications for both human integrity and asset integrity. Figure 2 shows the dilemma of a SMART maintenance system in a railway context. On one hand the rolling stock must reach a certain destination. On the other hand one alarm comes up as a potential threat to the functional integrity of the vehicle, maybe for people travelling on it and finally for the business. The maintenance engineer r must prioritize the maintenance actions to be taken as a function of the acceptable risk, and sacrifice either the vehicle or the business goals, since human integrity cannot be neglected.

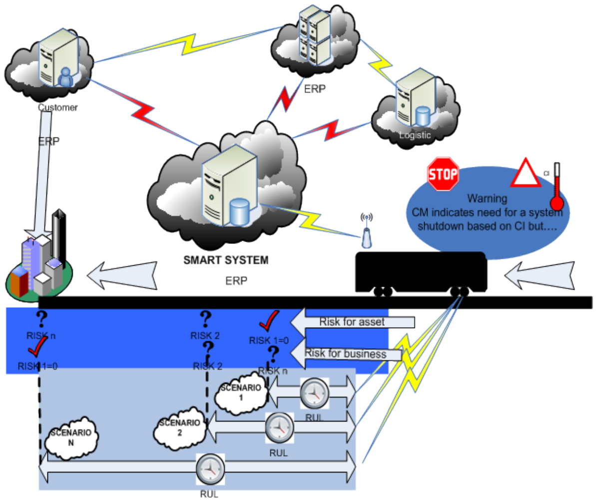

Figure 2. SMART maintenance system in railway

The criteria used to evaluate risk-based decisions are moving from a pure economic perspective to the consideration of social and environmental factors to protect humans and assets (Wolff et al., 2000). This entails that asset maintenance practices, must be comprehensive to encompass financial performance assessment as well as environmental protection and societal impact (Liyanage & Kumar, 2003).

B. Role of risk in SMART bearings

In conclusion, the most important steps in the procedure for risk assessment are summarized in Fig. 3. In particular, the role of models and methods for reliability evaluation and maintenance is clearly emphasized. The concept of SMART maintenance proposes a plant integrity management based on Risk Based Maintenance (RBM) as an extension of the well-known and establish Risk Based Inspection (RBI) for risky and hazardous industries like oil and gas (API 580 and 581). This is an integrated approach to risk assessment and maintenance planning. Ad hoc rules for planning inspections to balance acceptable risks of failures versus mission accomplishment and improve safety and health, reduce costs by repair or replacement of deteriorating equipment at the optimal time and eliminating ineffective inspections or interventions.

Consequently, SMART bearing concept proposes models and methods for supporting managers and practitioners in planning and executing maintenance actions in the framework of risk-based maintenance since all stakeholders accept that maintenance decisions involve the acceptation of some intrinsic risks. Therefore SMART devices must have embedded methods for aiding in the decision concerning maintenance operations on assets and individual components. This assessment method is the core of SMART bearings providing the decision support system mechanism and at least must comprise the following steps:

a. Analysis of the degradation of the components;
b. Evaluation of the functional consequences, for the asset, of the analysed degradation according to the scheduled utilization of the machine; and
c. Determination of an operational of the asset according to the evaluated functional consequences.

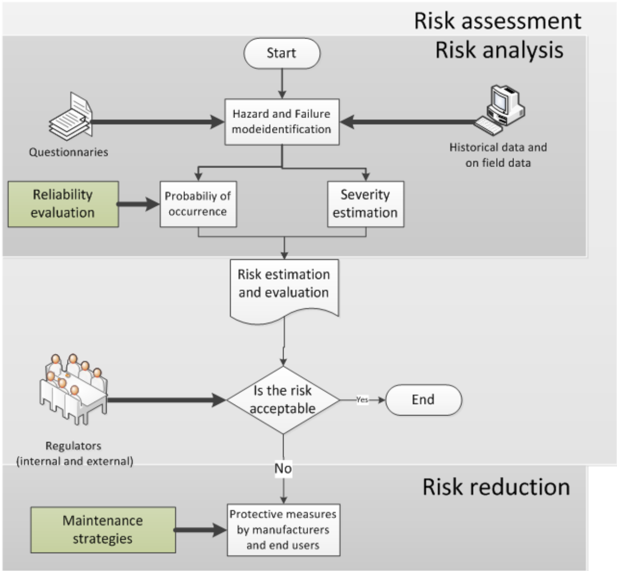

Figure 3. Flowchart of risk assessment

The method to assess this risk should make it possible to optimize the maintenance operations on a bearing according to its utilization by determining an operational risk, or in other words a risk of disturbance of normal utilization. The operational risk is based in particular on a prognosis of failure of at least one component, this prognosis being determined by analysis of degradation of this component.

The assessment should comprise the calculation of two relevant parameters. On one hand, the determination of a functional state of at least one of the components (critical), and on the other hand the determination of an operational index of the asset based on the evaluated functional consequences and on the functional state, in order to improve the maintenance operations by combining the diagnostic and prognostic functions concerning the asset components.

The first parameter will show the degradation of at least one of the components preferably must comprise the estimation of the degradation trend of at least one of the components and the evaluation of a probability of breakdown of these components.

The second parameter will display the measurement of the risk. The evaluation of the functional consequences and analysed degradation according to the scheduled utilization of the asset will be connected with first parameter through a predefined failure model. The failure model can be determined by theoretical analysis or according to a statistical method based on observation of the behaviour of similar components of the same asset or of similar assets.

These techniques are based on information on potential degradation mechanisms and threats obtained by a risk analysis, and not only by prescriptive practices generally based on industrial experience (e.g., historical experience, industry guidelines for classes of equipment, as a prescribed percentage of the estimated residual/remnant life). These analytical models are basic, but they can effectively support the development of ad hoc supporting decision making methods for the analysts, owners, and users (e.g., safety managers, site inspectors, the so-called competent person, duty holders) of many industrial and service companies.

III. Diagnosis and prognosis as maintenance DSS enablers: Risk assessment

Diagnostics is an intrinsic and valuable element of asset health assessment. Its applications and contributions to the quality of maintenance are expansive across all aspects of asset management. Beyond the value to individual machines, diagnostics also contribute to the improvements of production systems and development of new technologies in different sectors. Diagnostic tests serve a role in the measurements and tracking of standards and quality of maintenance by maintainers and end users, underlying their essential and multifunctional contribution to machine health. In addition, the protection of the machine health relies on diagnostics to detect non-visible damage that reduces the Remaining Useful Life (RUL) of the asset.

Diagnosis and prognosis information are indispensable for decision-making by maintainers, end users, manufacturers even regulators. The decisions are made for asset specific and population wide treatments, measures, procedures, and services. Diagnostics/prognostics provide key and sometimes critical information at multiple junctures along the life cycle, from risk assessment and early diagnosis, to machine follow-up and breakdown management.

The principal uses of this information include diagnosis, primary risk assessment (i.e., predictive and early problem identification), prognosis, selection of corrective action if needed, selected condition monitoring and deterioration management. Diagnostics/prognostics provide maintainers with information essential to taking appropriate decisions.

A. The dilemma of concurrent failures

In diagnosis, one or multiple tests are used, typically in combination with machine history and technician experience, to identify a particular existing problem or condition. Some tests or test combinations may identify the existence of multiple degradations and machine health problems in addition to the primary diagnosis, providing information that can inform selection among alternative actions or adjusting a selected treatment. See Figure 5a where a centrifugal pump exhibits a vibration velocity spectrum with multiple damages of different severity like unbalance, misalignment, looseness etc… on the other hand 5.b shows an identical machine which just shows unbalance in the rotor. Unfortunately 5.a is much more frequent than 5.b and maintenance response must be entirely different in function of exiting problems, their severity and how they are combined among them.

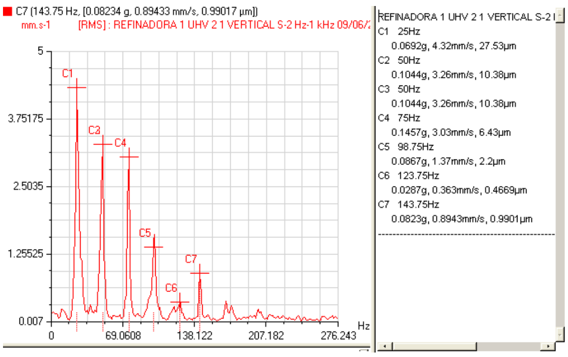

Figure 5a. Spectrum of an asset with multiple pathologies

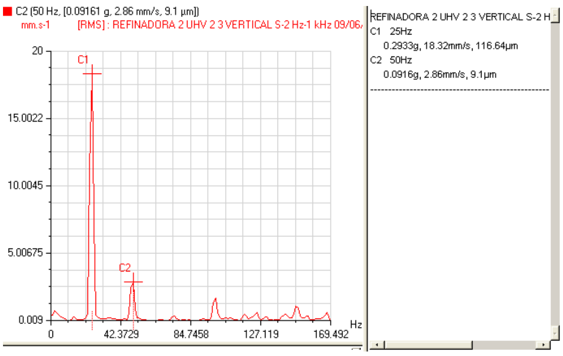

Figure 5b. Spectrum of an asset with one identified problem

In fact, this dilemma about what is happening in the asset is more dramatic in the bearing. When a rolling bearing rotates under load the contacting surfaces of the rolling elements and the raceways normally become somewhat dull in appearance. This is no indication of wear in the usual sense of the word and is of no significance to the bearing life. The dull surface in an inner or outer ring raceway forms a pattern called, the path pattern. This pattern varies in appearance according to the rotational and loading conditions. By examining the path patterns in a dismantled bearing that has been in service, it is possible to gain a good idea of the conditions under which the bearing has operated. By learning to distinguish between normal and abnormal path patterns there is every prospect of being able to assess correctly whether the bearing has run under the proper conditions.

In the majority of cases the damage to the bearing originates within the confines of the path patterns and, once their significance has been learned, the appearance and location of the patterns prove to be useful aids in diagnosing the cause of the damage.

Each of the different causes of bearing failure produces its own characteristic damage. Such damage, known as primary damage, gives rise to secondary, failure-inducing damage – flaking and cracks. Even the primary damage may necessitate scrapping the bearings on account of excessive internal clearance, vibration, noise, and so on. A failed bearing frequently displays a combination of primary and secondary damage. The types of damage may be classified as follows: Primary damage, wear, indentations, smearing, surface distress, corrosion, electric current damage, secondary damage, flaking and cracks

In summary, there is a well-known catalogue of damages that can be identified in a bearing. The real problem is the concurrence of several problems simultaneously overlapping and masking each other what makes the identification of the most severe extremely complicated. Therefore, proper diagnostics becomes essential to identify the real or most severe reason of the current deterioration.

B. The benefits of accurate diagnosis

Diagnostics can detect incipient problems or determine which bearings are at increased risk for developing certain deterioration. Determination of increased risk may allow maintainers to take measures to prevent or reduce the risk of developing a non-desired condition, including increased condition monitoring, operation changes, and preventive interventions.

Detection of emerging deterioration before symptoms appear or at an early symptomatic stage allows significant opportunities for early prevention and treatment. Accurate and early detection and identification of these mechanisms enable assessment of machine health status that can translate into reduced shutdowns, life-cycle cost, improved operation, and reduced maintenance costs. Diagnostics are evolving continually to enable more sensitive and specific detection of failure mechanisms at earlier stages via measurement of multiple parameters. These diagnostics offer new opportunities for timely damage prevention and treatment.

Consumer expectations for diagnostics, such as rapid results, increased automation, simpler operation, and enhanced portability continues to drive the development of SMART bearings. SMART diagnostics will play a significant role in maintenance decision-making, particularly in areas where rapid and accurate response is closely tied to outcome such as the diagnosis of an imminent failure.

C. The importance of the context

RUL of a bearing is commonly calculated using the work of (Lundberg & Palmgren, 1947) considering mainly load and rotation speed. This successful equation comes from Weibull analysis and reflects a prediction of units in a large population. Nowadays there are much more data available to consider in RUL estimations. The “profile” (manufacturer, environment, operations...) or other predispositions of a machine may influence the individual's response to a maintenance action. Emerging maintenance technologies use information about asset variability to allow targeted treatment selection tailored to individual needs. Context diagnostics are profile-based diagnostic tests used to determine the individual benefits or losses associated with various alternatives available for various actions or decisions . The knowledge of targeted treatments can allow the maintainer to avoid taking potentially harmful or ineffective maintenance actions for assets, resulting in improved machine health outcomes and cost savings resulting from more effective decision-making. Context based decisions is facilitating an ideological shift within the maintenance community from a "one size fits all" treatment approach to that of "right maintenance actions for the right machine." Databases that compile and present such information are becoming available for scientists to study and maintainers to understand how profile variations may relate to actions outcomes. As the use of context data becomes more integrated into maintenance practice guidelines, electronic records, and decision support systems, will increasingly include context-based policies in routine treatment decisions. The increasing use of context technologies holds great potential to yield better treatment selection and failure management strategies.

Diagnostic tests also may be used to assess the degree of damage progression or severity and the likelihood of recovery or risk of future adverse outcomes. The prognostic information frequently is used to inform treatment decisions tailored to individual machine health status and needs. Prognostic assessment can include testing for certain co-existing problems (e.g., unbalance, misalignment, wear, oil problems). The presence of co-existing failure mechanisms may inform necessary alterations in maintenance options and operation regimen. Certain chronic failures require continuous monitoring to avoid serious consequences or maintenance complications, so screening for emerging resistance to maintenance actions or co-occurring failures is essential. Commonly used for these purposes, diagnostics are instrumental in helping maintainers manage complex, or later-stage machine health problems or conditions. Effective failure monitoring and management often is linked to reduced maintenance utilization, maintenance costs, and improved operation.

SMART bearings, with contextual capabilities, based on Real Time Condition Monitoring and optimum Decision Support Systems, will allow maintainers to conduct rapid diagnostic in situ tests, rather than sending data to centralized laboratories. Such rapid diagnostics will provide technicians with information on machine health status and maintenance options during the maintenance inspections or scheduled actions. This immediate responsiveness will reduce delays in effective decision-making, allow rapid response to critical situations such as sudden breakdowns due to fast degradation mechanisms, as well as routine and non-critical situations so will be able to reduce maintenance department costs.

D. Network of SMART bearings

The existence of large population of SMART bearings performing diagnosis and prognosis will have a global benefit as well. In a first stage this info will be useful to detect problems in individuals and later, for tracking population-level outbreaks. There is a number of applications for population diagnosis, including global degradation, transmission of problems, identification of common failure mechanisms or resistance to maintenance (preventive or corrective) actions in order to determine future risks. As novel diagnostics continue to emerge in this area, machine health threats can be characterized and contained more quickly and efficiently, affecting fewer individuals in improving health management options. Use of diagnostics for these applications will inform appropriate maintenance decisions and containment efforts to reduce the spread of the failure mechanisms along the bearing population. Diagnostics development in this area has focused on rapid and accurate results, as well as portable, easy-to-use instruments. Technological advances increase flexibility and responsiveness to changing maintenance needs. Newly developed rapid detection diagnostics may help decrease the time between introduction of a new failure mechanism and detection, enabling faster and more effective maintenance response. Many of these emerging diagnostics also are being adapted for field use in emergency situations, ideally allowing containment efforts through self-maintenance actions (via actuators) to begin before maintenance crew comes into the picture.

Emerging technologies, such as tribotronics, are useful for associating expression of various products with oil status or machine health. As new markers are validated, and as the significance of various combinations of markers are better understood, these technologies are being adapted rapidly for a range of diagnostic applications. One expanding trend is multiplexing, which involves conducting tests for more than one marker in the same test sample. This testing paradigm also is being developed in array formats, where multiple multiplex tests can be performed on the same platform or chip. This availability of data is good in essence but simultaneous acquisition of large amount of data can produce a non-desired effect of prioritization of data storage and transmission rather than data analysis and info extraction. For this purpose, data fusion becomes essential to combine acquired info and prune the one that is redundant or useless.

As diagnostics become increasingly integrated and capable of generating vast amounts of data, analytical advances and ease of interpretation will better facilitate adoption and diffusion of these technologies into routine maintenance practice. For example, interpretation of tribology marker assay that includes several hundred tests may be too complex for use in general maintenance practice without software or information processing capabilities to assist with analysis and presentation of diagnostic results. As products that identify many hundreds or thousands of markers, sophisticated analytical tools will be necessary to decipher the relationships between collected and processed information versus predisposition to initiate the failure mechanism.

Advances in electronic maintenance records and decision support software, will assist maintainers in extracting meaning from increasingly complex diagnostic results. Computerized systems and networks are currently assisting with processing certain tests, and similar systems will decrease diagnostic interpretation time, allowing for more rapid translation into appropriate prevention or treatment efforts.

The impact of diagnostics is undisputed as an essential role in the life cycle of an individual, the general population, and the environment. The significance of diagnostics is anticipated to increase as it evolves with other interventions and with machine health information technology. Cloud computing interfaces are anticipated to better link together the profiles of machines, technicians, end users, manufacturers and regulators, (Galar et al., 2012). The new diagnostic interfaces have the potential to redefine, on a global scale, the relationship among these participants through timely and relevant information available at the "fingerprint", (Wandt et al., 2012). The convergence of diagnostics and machine health information technology will be the driver of the development of more rapid, accurate and high throughput diagnostic information.

SMART bearing, as future self-diagnostic devices will have a need to incorporate advanced information technology with greater integration capabilities, ease of use, and compatibility with other instruments or information resources (e.g., electronic records or databases). Despite current advances, portable diagnostic devices, for example, instruments or field use devices, still lack features, flexibility and capabilities to further enhance the ability for maintainers and end users to capture, interpret, and use diagnostic information with greater speed, precision, and context. In fact energy consumption, transmission and configuration are some of the issue that SMART bearing project must overcome.

Conventional diagnostics provide minimal information such as a numerical value to a maintainer but minimal contextual information as to the potential relevance of the result at a higher plane of observation. The majority of conventional diagnostics also fall short of providing rapid real-time assay results which is an essential element for time critical diagnostic decision-making.

The recent technology development using SMART bearings will enable rapid and highly sensitive diagnostics for a wide variety of tests. The capabilities of these diagnostic technology platforms, when combined with advances in computing, telecommunications, and satellite technologies will enhance the capacity and the potential of diagnostics, setting a stage for a paradigm shift in the generation and management of machine health information and services.

IV. Decision-making Strategy: Risk reduction

Fault detection and diagnosis, in general, are based on measured variables by instruments and observed variables and states by human operators. The automatic processing of measured variables for fault detection requires analytical process knowledge and the evaluation of observed variables requires human expert knowledge which is called heuristic knowledge. Therefore fault detection and diagnosis can be considered within a knowledge-based approach, (Rasmussen, 1993, Struss et al., 1996, Isermann, 1994). Figure 6 shows an overall scheme of the proposed architecture for SMART bearing concept.

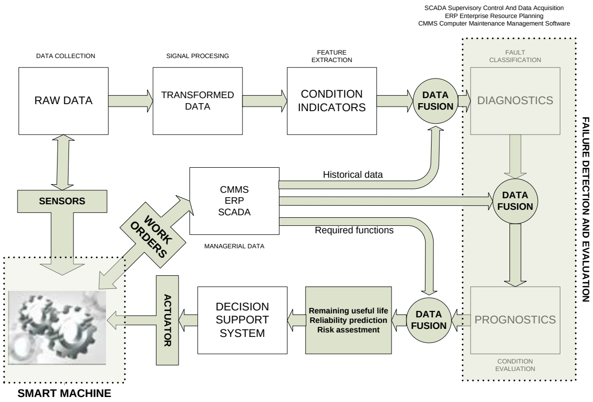

Figure 6a. Proposed SMART architecture

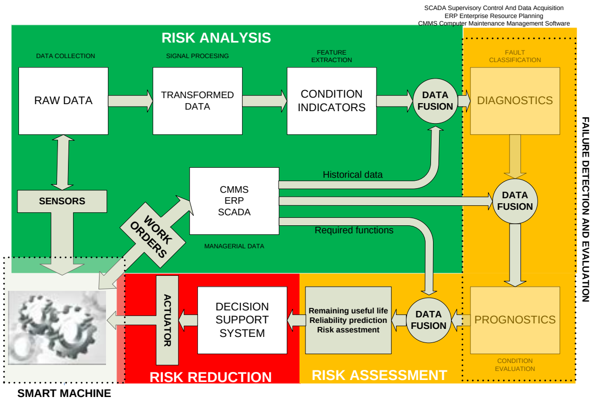

Figure 6b. RISK stages in SMART architecture from identification to mitigation

In the first phase, the selected sensing elements for test array must be deployed together with its power supply, integrated computing and its wireless communication with the surroundings. There are common condition monitoring techniques like vibrations, ultrasound, oil analysis or thermography with increasingly less expensive acquisition systems, but besides these parameters, others provided by passive electrical sensing (inductive, resistive, and capacitive), active electrical sensing (electromagnetic fields, piezoelectric) can also reflect the condition of some parts of the bearing. These sensing techniques should be also used to measure the operating conditions (speed, load, temperature) in order to configure the fingerprints and create the context records. The empirical relationships between sensor output and actual physical condition must be established but there are multiple ways to do it.

Information extracted from the sensors can be manipulated in different ways. Some relation between variables values and potential consequences with mitigating actions can result from personnel experience - mostly maintenance crew and operators who know the behaviour of the machine. This information is valuable and there are many efforts to retain this knowledge within the companies due to the ageing effect of maintenance crews all over the world. However the relations between acquired data and existing fault for further decision making aims to be a model. Only reason for that is the systematization and automation of diagnosis and prognosis with optimum maintenance decision making.

Models can be data driven or physical based modelling, (Galar et al., 2012). Data driven provide a black box approach where acquired data are processed and a number of features are calculated in order to find those with peculiar behaviour, anticipating anomalies and malfunctions of the asset. Alternatively, physical models use physics of the failure to mathematically model the failure mechanism in order to identify it first and predict how long will last, later. According to Galar et al., 2012, the information fusion of such relevant sources, models and maintenance experience can provide a powerful tool where the weaknesses of both methods are compensated among them.

The hybrid models proposed in the SMART bearing approach consider the analytical knowledge about the process to produce quantifiable, analytical information. To do this, data processing based on measured process variables are performed to generate first the characteristic values by:

a. Limit value checking of direct, measurable signals. The characteristic values are the violated signal tolerances usually the result of experienced technicians and operators.
b. Signal analysis of directly measurable signals by the use of signal models like correlation functions, frequency spectra, autoregressive moving average (ARMA) or the characteristic values, e.g., variances, amplitudes, frequencies or model parameters. These techniques together with AI tools like ANN, SVM or LSM constitute the basis of data driven methods for diagnosis and prognosis
c. Process analysis by using mathematical process models together with parameter estimation, state estimation and parity equation methods. The characteristic values are parameters, state variables or residuals. Information provided by the process and properly modelled constitutes the foundation of physics based methodologies.

Features are extracted, e.g., physically defined process coefficients or special filtered or transformed residuals and then compared with the normal features of the non-faulty process. For this, methods of change detection and classification are applied. The SMART architecture does not neglect the potential benefits of both data and physics driven methods. The resulting changes (discrepancies) in the directly measured signals, signal models, or process models are considered as analytic symptoms.

The real challenge is the comparison itself and the concept of discrepancy. Maintainers and end user usually wonder how big should be the increment of a variable to consider it as a real threat. Actually, this consideration is the first step of the decision making process as the detonator for maintenance actions if risk is really present or just a false alarm due to the natural ageing process of the asset. Figure 7 shows a taxonomy of analytical fault-detection methods.

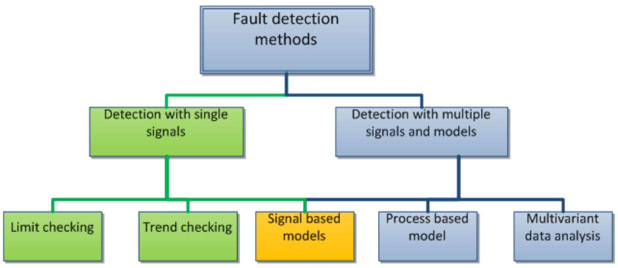

Figure 7. Analytical fault detection methods

Once comparison is done and diagnosis and prognosis performed, it is time for the decision itself i.e the maintenance action. This action can be a self-lubrication, self-alignment or any other task designated to reduce the risk of failure and mitigate the degradation. This stage of the risk is the most complex. Previous research has been successfully done in risk analysis for bearings (i.e. condition monitoring and anomaly detection), however the risk assessment as a deep analysis of the diagnosis and prognosis with consequences of the breakdown and accurate timing estimation are more seldom. Finally, few researches have been done in the systematization and automation of the actions as a consequence of this assessment. Risk mitigation closes the loop started with risk analysis and constitutes the core of SMART bearing project.

V. Conclusions

The future development in bearing technology will be dependent on development of smart condition monitoring and maintenance solutions by smart use of IT. Risk assessment of alternative maintenance decisions based on RUL estimations provide a promising strategy to evaluate the different consequences of performed maintenance actions, or deferred maintenance. This methodology relies on collected information, creation of the operational scenarios and potential deviations from expected behaviour. Underlying technologies like sensors and algorithms must be properly connected, and preferably according to existing standards if any.

However these risk assessments policies are very seldom in maintenance and most of the existing ones are focused on the protection of human being and environmental impact. It is time to redirect safety issues towards asset integrity and accomplishment of business goals besides human safety.

Technologies are very similar and already available; however there is a lack of standardization which will be hopefully sorted out with the upcoming ISO 55000 2012a, 2012b & 2012c.

Acknowledgements

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