TRIBOLOGY IN RELIABILITY ENGINEERING

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SUMMARY
The tribological understanding of friction and wear mechanisms and the generation of reliable friction and wear data are of increasing importance for the determination of reliability of machinery and availability of plants and transportation systems. To be of real value in reliability engineering, the tribological data should be expressed in terms of endurance life and probability of failure. The minimum coefficient of friction and the minimum wear data are important scientifically and for optimal design and material development purposes, but they are of less relevance in reliability estimation. The scaling-up of our tribological knowledge from nano- and microcontacts to solid performance estimations and reliability predictions of large machines is a major challenge for the tribological society.

Keywords: reliability, tribology, design, monitoring, scaling

1 INTRODUCTION
A general trend in our society is to develop larger and more advanced technical systems which are at the same time more complex and difficult to control. The availability of plants and transportation systems and the reliability of machines and instruments is of increasing importance. The failure of technical systems may result in safety risks, and in large environmental risks. Breakdowns in the industrial production process are expensive for the industry and the whole society. There is an increasing need for improved methods of determining the reliability and predicting the lifetime of machines and production systems more accurately.

Mechanical failures of components and especially tribological failures, such as wear and friction-related failures, are today one of the main reasons for machinery break-down, plant shut-down and equipment unavailability [1−5]. This paper deals with the role of tribology in the large and complex scope of reliability engineering, the different tribology-related methods that exists to improve reliability, and finally the scope of tribology covering technical and scientific problems from nanoscale up to terascale.

2 A HOLISTIC APPROACH TO RELIABILITY

Since there is a great variety of different techniques based on expert knowledge in the several fields of technology involved, there is a need to approach the reliability and maintainability problems from a general holistic point of view starting from the problem of the customer and ending with the satisfied user [4, 6]. This is aimed at improving the synergistic interactions between the different fields of expertise by showing a logical and comprehensive structure, where each expert can find his place and see the connections to experts from other fields, all working with the same aim of well controlled risks, failure frequency and lifetime, as shown in Figure 1.

![Figure 1: A holistic systematic approach to the improvement of the operational reliability, availability and safety of products and industrial production systems.](image_url)
3 COMPONENT RELIABILITY

The basic tribological phenomena – friction, wear and lubrication – are all reliability-related. Friction in machinery and equipment resists motion and can result in energy losses and failure. Wear is a process of material deterioration that will result in failure if it can proceed far enough. Lubrication is the method of controlling friction and wear by introducing a third material between the interacting moving surfaces, which can reduce energy losses and help avoid failure [5, 7].

One major challenge for the tribology society is: How can we produce better tribological data of interacting components to support actions for improved reliability? In this context, it is not so important to find out what is the minimum coefficient of friction that can be achieved in a certain case, since it is not the situation with minimum friction that is problematic. The risks of failure and shut-down appear when the design value of a coefficient of friction is exceeded, thus creating higher frictional forces that may cause damage or stop intended mechanical movements. Similarly, the low-wear situation is not the problem, but a problem may occur when the wear rate for some reason exceeds the values in the design specification; this situation results in geometrical changes and changes in tolerances between components, and thus in possible inaccurate or even hazardous movements or failures and shut-down.

What is important from a reliability point of view is to produce more and better tribological data on the endurance life and on the critical wear and friction levels of tribological components, both in general and in specific operational conditions.

Figure 2a illustrates schematically three situations of component wear. In the first situation, severe wear is starting already at an early stage of the operation due to unsuccessful design. In the second situation a mild wear condition is achieved after a running-in wear period and a considerable safe operating time prevails until the slowly proceeding wear damage of the surface results in severe wear.

Finally, in the third situation successful design has produced a contact condition, which, after a short running-in wear, results in a long period of insignificant wear. The repeated contact load will ultimately result, however, in fatigue failure and catastrophic wear [8].

![Figure 2: An increase in wear and friction may with time exceed the critical wear and friction levels and then the operation is in the risk zone for total failure and shut-down.](image-url)
The important question from a reliability point of view is to produce tribological data and techniques with which the endurance life can be estimated. The endurance life is the time until the component can no longer perform its planned function. The designed endurance life is the time until the cumulative wear limit for safe operation specified in the design specification, the critical wear level, is exceeded in operation. Similarly, as shown in Figure 2b, the changed contact conditions can result in exceeding the endurance life when an increase in the friction force exceeds the values in the design specification, the critical friction level, and a risk for safe operation occurs.

4 TRIBODATA FOR RELIABILITY ASSESSMENT

There are four ways of getting the required tribological data for the estimation of component endurance life and risk for failure. They are: by collecting historical data about how similar components have performed in similar operational situations earlier; by using the generic knowledge of tribological behaviour in theoretical models and equations; by laboratory testing of components and materials, and by on-line monitoring of the tribological performance.

There is a lot of knowledge and experience to be gained from observations of how similar components have performed earlier in similar conditions. One problem is of course that often the earlier operational conditions may be more or less different from those to be estimated, and thus the interpretation of the results includes uncertainties. But the main problem is, however, that today in almost all areas of industry this information is not collected in such a systematic way that it can easily be used for endurance life prediction. The history data of used components is often collected mainly for the use of legal safety or compensation-related needs. To be useful, this data should be collected by using operational and failure codes especially developed for reliability estimation purposes [1, 9].

The quantitative friction and wear modelling that is possible to do based on today's state-of-the-art techniques has a large variation in the level of accuracy. In some areas, such as in the calculation of surface stresses or in the calculation of elastohydrodynamic contact pressures and film thickness, there are quite advanced and precise mathematically formulated models. On the other hand, there is no model available for the estimation of friction or wear in contacts with coated surfaces in the presence of a fluid containing contamination particles. Although a great number of equations for friction and wear in dry sliding situations have been proposed, their field of validity is still limited to only some certain contact situations [10, 11]. Here, the most promising approach for producing useful tribological data for reliability estimations is, in the authors' opinion, not to use generic wear equations but to develop component-specific friction and wear models. In such a way, the geometrical and material-related parameters can be fixed to a certain degree, and the number of fluctuating variables can be limited to a controllable level.

The laboratory testing of material combinations in specific contact situations and environments is today perhaps the most reliable way of gaining basic tribological data for reliability control purposes. It is essential that the experiments are planned and performed specifically for estimating endurance life, as discussed above. In addition to endurance life, another reliability parameter that is important from a practical point of view is the probability of failure. The tribological data can be of crucial value to the machine users when both the endurance life and the probability of failure can be expressed in statistical terms. The established experimental design techniques [3, 12] can be put to good use here, and they should be utilised in tribology laboratories much more.

When more reliability-related tribological data is available, it makes it possible to classify it and to systematically present it in similar forms as have been done in the mapping of friction and wear data [13,14]. The maps are useful when we have first managed to identify the two most dominant parameters on friction or wear and then produced the map with these two parameters as co-ordinate axes. Then we can place in the map the window for planned operational conditions defined in the design specification. It is obvious that for safe operation there should be no serious transition regions between different contact mechanisms in the operational window. Defining the operational window in tribological performance maps makes it possible to calculate the expected variations in endurance life and the probability of failure within this window, and if required, also when moving outside the operational window.

The aim should be that we can express our tribological data in a way such as: "the endurance life of the component will be more than 8 years with a 95% degree of confidence" and "the probability of operation without failure during the first three years is more than 98%". With this kind of basic reliability data of components it would be possible to estimate with a good degree of accuracy the reliability of machines and the availability of machinery systems and plants. This information is essential in situations when decisions on new investments, investments in diagnostic tools and redundancy equipment, and decisions on unscheduled shut-downs for repair have to be made.

5 CONDITION MONITORING AND DIAGNOSTICS

During operation of machinery, actions can be taken to improve the reliability and tribology has an important role to play in this. By condition monitoring of the performance, on-line information is obtained about the stage of functional deterioration that may be due to, e.g. the wear of surfaces. The area of condition monitoring and diagnostic engineering today is an advanced and highly developed field of engineering [1, 2]. It includes the development of sensors to measure changes in
performance, data collection, signal processing, diagnostics, prognostics and maintenance engineering, as shown in Figure 3.

Particularly in the area of diagnostics, many new software tools have been developed for automatically performing appropriate conclusions based on the received on-line performance information [15]. Such new tools are expert systems, fuzzy logic, pattern recognition and neural networks. The next step after having made a proper diagnosis of the condition of the machine is to predict how the performance will proceed depending on what measures are to be implemented. This kind of prognostics is very important support for decision-making in situations where the consequences may be great or serious. The last part of the chain is maintenance engineering, which includes the knowledge of different corrective actions that can be taken based on the information obtained.

However, the whole chain from the signal detection by the sensor to prognostics and maintenance decision-making is of relevance only if the analysis of the signals is based on a solid knowledge of the phenomena observed. This is where tribology comes in. It is most important in the case of friction and wear-related monitoring that a solid understanding of the tribological contact mechanisms forms the basis for the signal processing, the diagnostic rules and the prognostic predictions. Unfortunately, this is not always the case today. Too often the engineers are satisfied with managing to monitor some kind of signal and then believing that advanced software techniques can produce correct conclusions. Only by bringing good tribological understanding about the mechanisms behind the functional deterioration observed can reliable predictions be made.

The most common machinery condition monitoring techniques used today are vibration analysis and oil analysis. These are both very much related to the tribological contact phenomena and a good tribological understanding is essential. Other condition monitoring techniques are performance measurements, such as measuring rotational speeds, forces, displacements, temperatures etc. [2].

6 RELIABILITY-BASED DESIGN

The design methods in use today are mainly based on performance calculations and static or dynamic load and durability analysis. New tools have recently been developed that also take into account the reliability aspects in design. One such tool is the reliability-based design method developed by Virtanen [9,16]. The method enables the effective prediction of the reliability of a product in explicit form right at the design stage and to use it, e.g. during the contract negotiations with a customer. This method provides a design team with the means to judge new and innovative ideas on the basis of their predicted reliability, and it helps the team to focus on the right target with their reliability engineering efforts. The method also offers the possibility to analyse the customer’s view of reliability requirements and to compare this with what is technically possible to achieve, as shown in Figure 4.

![Figure 3: Condition monitoring and diagnostic engineering is a multi-technological task. Tribology is involved in the failure mechanisms, diagnostic analysis and the prognostic predictions.](image-url)
The right-hand side of Figure 4 shows the process for specifying the reliability requirements and priorities of the customer for a specific product. This is quantified in terms of reliability parameters such as mean-time-to-failure (MTTF), mean-time-to-repair (MTTR), availability and maximum breakdowns. The left-hand side shows the process for calculating the same reliability parameters for the product based on the technical performance of the component and the system. This is a model-based simulation approach that starts with building up a fault tree for the product. The possible failures are estimated and classified according to best, mean and worst cases of probable occurrence.

The fault tree that forms the basis for the reliability simulation is based on failure data, diagnosis and prediction models. In the case of wear or friction-related failures, the estimation of the probability to appear during certain periods in the lifetime of the component and the estimation of the probable endurance lifetime is based on the best available tribological data. This data can be obtained from historical data analysis, from theoretical models or from laboratory-produced data, as described above. To be of use for the model, the data should be presented as reliability-related parameters.

This emphasizes the importance for the tribology society to produce friction and wear data for different material combinations, as well as in different contact and environmental conditions in the form of endurance life or probability of failure. The data can then be of use in reliability estimations and functional predictions of components and machines. It is actually not very useful at all if only the minimum achieved coefficient of friction and the wear rate are known.

7 FROM NANOTRIBOLOGY TO TERATRIBOLOGY

Relating tribology to machinery reliability and to plant or transportation availability is very important and responds to the increasing demands of both industry and society. However, it is a great challenge to scale up the knowledge we have on the friction and wear mechanisms from tribological studies, which are typically made on a micrometer scale in tribometers and microscopes, to component and machinery systems that can be as large as ferry boats or paper machines.

In tribology today we can see another trend, which is to go to smaller and smaller sizes in the investigation of friction and wear phenomena. Nanotribology is of increasing interest for tribologists and here the scales are coming down to the very basic dimensions of physical elements such as atoms and molecules [17]. Emerging technologies such as the atomic force microscope and the surface force apparatus [18] have recently opened the possibility to study friction and wear phenomena on a molecular scale and to measure frictional forces between contacting atoms at a nano-newton level. Increased computational power has made it possible to study friction and associated phenomena by molecular dynamic simulations of sliding surfaces and to investigate atomic-scale contact mechanisms [19].

![Figure 4: A novel reliability-based design method consisting of an advising reliability model and an allocation model for the customers dependability requirements (9).](image-url)
The increasing understanding of the tribological phenomena on nanoscale creates the need to scale up our nanoscale knowledge to conclusions on improved prediction of friction and wear that takes place on a more macroscopic scale, such as in practically observable everyday life. An attempt to illustrate the scaling up of the very basic friction and wear phenomena all from atomic dimensions to global and universal dimensions is shown in Figure 5 [20].

*Nano*tribology could also be called molecular tribology because here the investigations concentrate on phenomena related to the interaction between molecules and atoms such as the effects of van der Waal’s forces and single crystal structures of materials.

*Micr*otribology or *asperity tribology* was introduced by Bowden and Tabor [21] with their studies of friction, wear and adhesion that take place at the peaks of the surface topography. Phenomena such as fracture, elastic and plastic deformation, debris formation, surface layer formation and topography effects are of central importance.

*Macr*otribology or *contact-tribology* was in focus in the research at the beginning of the last century. These works are related to contacts between gears, bearing elements and rollers, and phenomena like Hertzian contact pressure, elastohydrodynamic lubrication, and wear mechanisms clearly observable by the naked eye (scuffing, scoring, pitting) are of interest.

*Component* tribology or *deci*tribology is related to defining and measuring typical parameters originating from the interaction of components and related to their performance such as torque, forces, vibrations, clearance and alignment.

*Machinery* tribology or *unit*ribology describes the performance-related phenomena for a system of components assembled in a machine or a piece of equipment. The parameters of interest are performance, efficiency, reliability and lifetime estimation.

*Plant* tribology or *kilo*tribology deals with a whole system of machinery, structures and equipment – and now parameters such as economy, risk levels, availability and life-cycle costs are considered.

*National* tribology or *mega*tribology extends the effects and consequences to be seen from a nationwide perspective, with the parameters of relevance such as safety policy, research policy, transportation policy and environmental policy.

*Global* tribology or *giga*tribology considers the effects on a worldwide basis as one interacting system; the effects that are dealt with are sustainable development, politics and cultural and human survival.

*Universe* tribology or *tera*tribology is the largest perspective today that the author can think of in this scaling up exercise. But what does this mean? Is it the inter-relations of material in our large space? Is it the mechanisms for space enlarging, or is it mechanisms for the creation of new life and cultures?

The scaling up from molecular phenomena all the way up to universe tribology is an interesting exercise because it shows that at all levels we have to do with phenomena that are known to us to some extent. In this sense, then, it shows that talking about ‘scaling up’ and ‘scaling down’ is relevant.
However, this exercise also has a considerable risk. It may give the impression that our whole universe is just a mechanical system, like a complex mechanical clock, and if we only knew all the details on the smallest atomic and even subatomic level and knew all the laws of interaction then we could calculate and predict what takes place nationwide and on a global scale. This is by no means the intention of the author. On the contrary, there are today indications and opinions that criticize such a mechanistic approach [20, 22, 23].

8 CONCLUSIONS
To be of real value in reliability engineering, the tribological data should be expressed in terms of endurance life and probability of failure. The minimum coefficient of friction and the minimum wear data are important scientifically as well as for the optimal design and material development purpose, but they are of less relevance for reliability estimation. The aim is to transform the tribodata to reliability parameters such as mean-time-to-failure (MTTF), mean-time-to-repair (MTTR), availability and maximum number of breakdowns per time.

It is possible to express tribological effects on different geometrical scales all the way from nanotribology, perhaps even up to teratribology. However the foreseeable scaling-up of our knowledge will probably need other more nonlinear approaches than the strict reductionism to which we are accustomed.

9 REFERENCES