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# WEAR ORIENTED STRATEGY FOR GEARBOX REMAINING LIFETIME ESTIMATION

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**Abstract**

Machine condition monitoring of equipment critical to the operation of a plant has become common practice in most industries, both for the detection and progress tracking of faults. Tracking the progression of faults is a measure of the rate of degradation which is often used as an indicator for assessing the remaining lifetime of the machine. The estimation of remaining lifetime without a dedicated strategy will however result in unreliable results. Knowledge of the remaining lifetime of a machine can aid the maintenance department in ordering appropriate replacement parts, plan a machine shutdown or machine replacement. Current techniques are generally concerned with the statistical distribution of failure, which is not always available and may be open to error.

A strategy for predicting the remaining lifetime of gearboxes is presented in this paper, based on the wear conditions of components detected by machine condition monitoring. While this strategy can be used to estimate machine lifetimes from new condition, this unique approach also allows the estimate to be updated using machine condition monitoring data. In this way, abnormal operating conditions such as overload and lubricant contamination can be included in the revised estimate. This allows the new strategy to better adjust for changes in operating conditions with potential improvements in accuracy over statistical techniques for this scenario. The strategy has been implemented in an expert system for machine condition monitoring and tested using a spur gearbox laboratory test rig. The benefits of this development promise improved remaining lifetime estimation by taking into account the actual operating conditions experienced by the gearbox to update the estimate. This allows an operator to predict the remaining lifetime of machinery and their associated components in a repeatable and objective manner.

## 1. INTRODUCTION

Machine condition monitoring has become a core component of many of today's maintenance programs, especially in machine intensive industries. Remaining lifetime estimation is a powerful tool for supplementing machine condition monitoring data, aiding maintenance departments in scheduling machine repair as well as deciding for optimum timing of equipment replacements. However, remaining lifetime estimation is commonly performed by judging the rate of fault progression as observed from the condition monitoring data. Due to the difficulty of assessing the true state and severity of a fault, this vague technique is prone to errors. The developments outlined in this paper deal with the estimation of lifetime by focusing on material wear of gearbox components, though the strategy could also be applied to other oil lubricated machines. Although wear has been found to contain statistical scatter, estimating lifetime on purely statistical results does not allow integration of machine condition data for improved accuracy [1,2]. The life estimation using a wear approach complements the information already obtained from a combined analysis expert system based on vibration, oil and wear particle analysis for further machine health analysis. The details of the expert system have been described in another paper to be presented at the conference.

The aim of this research was to develop a knowledge base that could be integrated into the combined analysis expert system that had been developed previously. It was considered crucial that a lifetime estimate could be obtained regardless of whether a machine fault or abnormal operating condition had been detected, as machines always wear even under normal operation. Due to the unpredictability of machine wear, it was considered important that the knowledge base contained mechanisms to either approximate the accuracy of the result, or provide a conservative estimate.

## 2. KNOWLEDGE BASE DEVELOPMENT

The knowledge base was developed to allow the use of common accepted and tested wear equations in an automated package for machine remaining lifetime estimation. Wear processes have been found to be extremely complex with many additional variables apart from load, speed and component hardness, which may have a significant effect on the calculated accuracy. Some of these factors include varying machine condition, differences in lubricants and component metallurgy, type and concentration of contaminants, and duty cycle of operation.

In order to develop a strategy for remaining lifetime estimation, a knowledge base for four common wear modes found in gearbox type machines was compiled. The wear modes focused on are comprised of abrasive, adhesive, cutting and sliding wear, the first two of which are discussed in the following sub sections. Although surface fatigue is also commonly encountered in gearboxes, this type of wear is dependent on cyclic loading and general overload, which can be detected easily by measuring the input power. By the time wear can be detected using oil and wear particle analysis, surface damage has already resulted. Additionally, surface fatigue propagates undetectable to vibration, oil and wear particle analysis until significant permanent surface damage has occurred. The remaining lifetime is therefore difficult to calculate without considering additional information such as gearbox power input and rated power to estimate the fatigue life.

### 2.1 Abrasive Wear

Abrasive wear occurs when a hard material abrades a softer material. The softer material is referred to the machine component undergoing wear, while the harder material is composed of either a rough hard surface or a soft surface containing a hard contaminant. This definition of abrasive wear therefore covers the two-body abrasive wear process. The three-body wear process is significantly more complex as it contains an abrasive particle in between and in contact with two softer surfaces. This results in increased variables, as the angularity and softer surface hardness may not be uniform, and as the abrasive particle may slide or roll between the surfaces. In view of reducing the complexity of the model to allow the remaining lifetime to be estimated, the use of two body wear approximation is beneficial.

The abrasive wear equation incorporated in the knowledge base was the common abrasive wear equation. Although this is a simple equation, it has been used successfully to approximate the wear rate in abrasive wear situations [3]. If the sliding speed and volume to be worn away are known in addition to the entities required for the equation, the remaining lifetime of a component can be estimated. Although this relationship remains true for all practical abrasive wear situations encountered, the impact of hardness and abrasive size on the resulting wear rate can change in certain scenarios. One example is when the hardness of the abrading material approaches the hardness of the abrasive, as could be the case when silicon dioxide (of Brinell hardness approximately 750 kg/mm$^2$) contaminant wears against steel (Brinell hardness of 200 to 1000 kg/mm$^2$). The effects of the hardness ratio can be included in the wear equation by using an appropriate wear coefficient, according to the graph shown in Figure 1. The wear equation developed to successfully calculate wear volume is [4]:

Wear Volume = ($K_{ABR}$ x Load x Distance) / Hardness

where wear volume is the removed volume of the softer material in mm$^3$,
$K_{ABR}$ is the abrasive wear constant as shown in Figure 1,
Load is the normal load in kg,
Distance is the sliding distance in mm,
Hardness is the Brinell hardness in kg/mm$^2$.

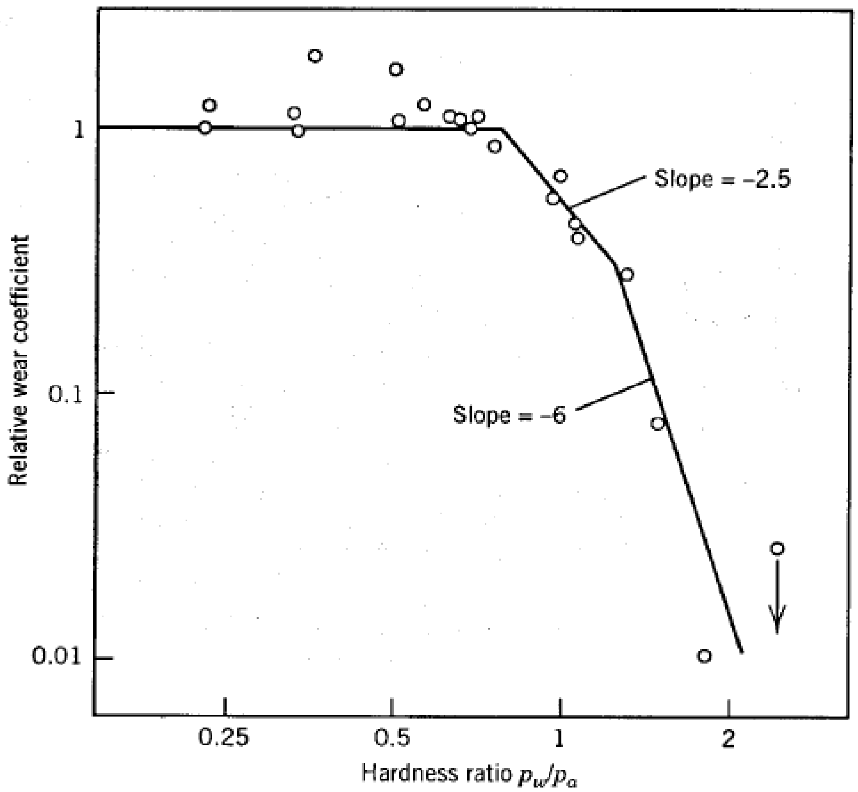

Figure 1. Variation of relative wear coefficient vs hardness ratio [4].

In order to use the wear equation for real spur gears as opposed to wear machines such as pin-on-disc apparatus, the sliding speed and sliding distance of the components must be determined. As spur gears are designed for rolling rather than sliding, the sliding speed component of the total rotational speed must be determined and used in the wear equation when calculating remaining operating time. This information is dependent on the type and design of the component, and was thus incorporated in the knowledge base by accepting the sliding speed as a percentage of the total operating speed. These specifications were thereby assumed to be available from either component manufacturers, or measured by independent tests.

### 2.2 Adhesive Wear

Adhesive wear is the process when two materials either of different or similar hardness slide against one another. In the case of two materials of differing hardness, more fragments and also of larger size are generally observed of the softer material. However, the harder material does usually also undergo wear although wear particles are fewer and smaller. One possible explanation to the harder material wearing is the existence of low strength regions within the harder material [4].

The wear equation used by the knowledge base is similar to that used for abrasive wear, except that the abrasive wear coefficient is replaced with the adhesive wear coefficient. The accurate calculation of the wear volume is dependent on the accuracy of the required entities, including the adhesive wear coefficient. While typical coefficient values for many different material combinations have been reported in literature, differences in lubrication conditions between the approximated and actual case can result in significant differences in wear coefficient [4]. This is evident in Table 1, showing the documented adhesive wear coefficients for metals. As the differences in wear coefficients are large for the different lubrication conditions, deviations from the four documented categories can greatly influence the accuracy of the calculated wear volume.

Table 1. Adhesive Wear Coefficients for Metals [4].

| **Lubrication** | **Metal on Metal** | | **Partially Compatible / Partially Incompatible** | **Incompatible** |
|---|---|---|---|---|
| | **Identical** | **Compatible** | | |
| Unlubricated | $1500 \times 10^{-6}$ | $500 \times 10^{-6}$ | $100 \times 10^{-6}$ | $15 \times 10^{-6}$ |
| Poor | $300 \times 10^{-6}$ | $100 \times 10^{-6}$ | $20 \times 10^{-6}$ | $3 \times 10^{-6}$ |
| Good | $30 \times 10^{-6}$ | $10 \times 10^{-6}$ | $2 \times 10^{-6}$ | $0.3 \times 10^{-6}$ |
| Excellent | $1 \times 10^{-6}$ | $0.3 \times 10^{-6}$ | $0.1 \times 10^{-6}$ | $0.03 \times 10^{-6}$ |

Lubricant additives can also affect the value of the adhesive wear coefficient, as the coefficient is dependent on the rate of oxide film formation of the wearing material, classified as the severity of wear [4]. If a metal oxide film can form as fast as it is worn away, the wear is classified as mild, while situations when the oxide film can not reform rapidly is classified as severe wear. Additives such as extreme pressure additives can therefore result in the wear regime to shift from severe to mild, as the oxide film can reform rapidly thereby influencing the adhesive wear coefficient.

High accuracy wear estimation using tabulated wear coefficients as shown in Table 1 is generally considered not satisfactory due to typical high statistical scatter of wear, and experimental error. However, the only alternative to improve the calculated wear volume is to determine the value of the actual wear coefficient by experimentation. While this can be done for critical machinery, it is not feasible for general condition monitoring of machinery unless this information is made available from manufacturers for the recommended lubricant. As the lubrication regime is also dependent on the load, the wear coefficient values from manufacturers would also need to include load limits to ensure that the machine operates in the desired lubrication regime. The knowledge base has been designed to accept a wear coefficient value from the operator which is then used for calculations. It is therefore the responsibility of the operator to supply a suitable value, either from the manufacturer, experimentally derived or tabulated.

## 3. REMAINING LIFETIME ESTIMATION STRATEGY

The details of the proposed strategy for remaining lifetime estimation are outlined in this section. It contains the strategy to update the estimate using the machine condition monitoring data, software implement of the strategy in an expert system, and the suitability of the approach using data from a laboratory test rig.

### 3.1 Knowledge Base Use for Lifetime Estimation

The developed knowledge base was designed to estimate the remaining lifetime of a machine, which enables the wear to be tracked and the estimate updated during the life of the machine. Due to the complexity of the wear processes, the general wear equations discussed in section 2 may have high variability and therefore only allow the remaining lifetime to be estimated. The estimate can then be updated using the condition monitoring data obtained from the combined analysis expert system, once machine faults have been detected.

**Determine Dominant Wear Mode**
(Abrasive wear)

⇩

**Calculate Remaining Lifetime at These Conditions**
(Based on the abrasive wear equation for the particular machine and operating conditions the expected life would be 500 hrs.)

⇩

**Determine Life Reduction During This Operating Period**
(The machine was operated for 10% of design life ie: 100 hours. As the estimated life due to the abrasive wear is 500 hrs, a life reduction during this period is 100/500 = 20%. This is equivalent to 200 operating hours during normal conditions.)

⇩

**Update Remaining Lifetime**
(At 200 hours lifetime of machine estimated at 800 hours.
New estimate = Old Estimate – Life Reduction = 800-200 = 600 hours)

Figure 2. Flow chart of calculation of remaining lifetime.
(Numbers are for samples of 200 and 300 operating hours of Table 2)

The wear equations allow the material volume worn away to be calculated given the core governing factors including load, sliding speed and material hardness, for adhesive and abrasive wear situations. It is therefore possible to calculate the remaining lifetime of a component when the permissible volume reduction due to wear is known. It is proposed that this volume can be determined by the difference between the dimensions of a new part (as manufactured) and the wear limits. Most manufacturers publish wear limits for components which govern whether a part can be re-used in a rebuild or whether it should be replaced. If these wear limits were used in the wear equations, it would be expected that the machine should still be operating when the component reached the limit, in most cases resulting in a conservative life estimate. The design lifetime of a machine may also be available from the manufacturer or from industry experience. The typical wear rate can therefore be determined, and used to correlate the percentage of volume remaining to be worn away with the estimated remaining lifetime in hours.

The life estimation using the wear volume approach as shown in Figure 2 can be performed on many parts of a machine monitored by oil and wear particle analysis, as long as the component only wears at one interface, and that the dimension only depend on wear. This therefore excludes the lifetime estimation of roller bearings which are press fitted into a housing and onto a shaft. The press fits can alter the internal clearances of the bearing, resulting in unpredictable wear volumes to be calculated using this strategy. This approach has been developed with a focus on the wear of spur gears and associated components, which satisfy these requirements.

Once the remaining lifetime has been calculated for each component or sub-component, the wear can be tracked over time by including the conditions of each operating period between oil changes. If for example a high contaminant concentration was detected during a known operating duration, the volume of wear for that duration can be calculated. The remaining lifetime can thus be updated for each oil sample, where factors including contaminant concentration and load variation are accounted for. The remaining lifetime can therefore be estimated using a spread sheet or database, noting the duration of each oil change period and the approximate percentage of total life that was used up in each period. A sample spread sheet is shown in Table 2, for a hypothetical case of lubricant contamination.

Table 2. Wear and Remaining Lifetime Tracking Using a Spreadsheet

| **Machine Hours** | **Operating Hours in Period** | **Wear Mode** | **% of Volume Worn Away in Period** | **Approx Remaining Life (hrs)** |
|---|---|---|---|---|
| 0 | 0 | Machine new | | 1000 |
| 100 | 100 | Adhesive | 10 | 900 |
| 200 | 100 | Adhesive | 10 | 800 |
| 300 | 100 | Abrasive | 20 | 600 |
| 400 | 100 | Adhesive | 10 | 500 |

Note: This example assumes design life of 1000 hours under normal elasto-hydrodynamic lubrication (adhesive wear mode), and shows the effects of abnormal abrasive wear during 200 and 300 operating hours.

The percent of allowable volume worn away in the particular oil change period can be calculated by the wear equation, and recorded similar as shown in Table 2. The values of this table demonstrate the effects of a period of contaminated oil at 200 to 300 operating hours resulting in abrasive wear can have on the remaining lifetime of a component. The remaining lifetime estimation is based on using an approximate machine lifetime that can be achieved under normal machine operation. The wear-in process is therefore accounted for in the lifetime estimate, and will appear in the lifetime tracking table as a region of higher than normal wear due to the typical wear-in wear modes, such as cutting and sliding wear. A similar scenario as the abrasive wear can occur if the component load is increased enough for the lubrication regime to change to a more severe level, such as boundary lubrication. The example in Table 2 has been incorporated into a flow chart shown in Figure 3, to illustrate the reasoning behind the proposed strategy.

The design life is the life determined by the manufacturer taking into account the typical operating conditions such as operating speed and load, as well as a suitable maintenance strategy. Fundamental gearbox design theory would base the design life on the surface fatigue life of the gear surfaces, and assuming the absence of contamination, or other component faults. The design life typically does not focus on the material removal at the wear-in, normal and wear-out stages. As the wear-in stage is a normal process that occurs with any new gear system, the machine life is not reduced more rapidly during wear-in than normal wear, even though the material removal may be greater during wear-in. It is therefore not necessary to include the wear-in stage in the life monitoring table, as shown in Table 2.

The information required to select the correct wear equation and corresponding wear coefficients is obtained from the report of the combined analysis expert system. The dominant wear mode can therefore be determined, and used to calculate the percentage of wear worn away during the oil change period. This method therefore allows the condition of all components in a machine to be tracked, and enables the remaining lifetime to be estimated. If the design lifetime and wear limits of the components and sub-components can be obtained, the life and cost of machine operation can be calculated, as well as the cost of the next machine overhaul. This information can be critical in deciding whether to overhaul or replace a machine, in order for cost efficient operation of the equipment in a plant.

### 3.2 Software Implementation

The knowledge base was implemented in the completed expert system code, and positioned in the menu system at the results page of the combined analysis expert system. As the dominant wear mode for each component is required for the remaining lifetime to be calculated, the positioning of this menu at the results page treats the remaining lifetime estimation as a further processing of the machine health. The remaining lifetime menu has been designed as a single input-output screen, with the operator being prompted with pop-up type windows for entering required information.

The remaining lifetime estimation algorithm has been included in the expert system package to utilise the potential benefits of this feature, as well as for research purposes to further improve the current algorithm. As the code is still considered in the development phase, it has not been fully integrated into the expert system in terms of sending data from the expert system results to the remaining lifetime algorithm. It is therefore necessary to manually enter the required information for each component or sub-component analysis. The required information is composed of the amount of material that can be worn away, as well as the entities of the relevant wear equation. This information could be stored in a text file and analysis performed automatically, as the analysis of vibration, oil and wear particle data. The current code also has no provision for tracking the remaining lifetime data for each component, as shown in table 2 for example. The output of the code could however be written to a text file in a spread sheet compatible format to allow more efficient data management. It is anticipated that these improvements would be performed when compiling the code into a prototype for commercialisation.

### 3.3 Application of Strategy

The remaining lifetime estimation strategy outlined in this paper was applied to condition data obtained from a single reduction spur gearbox test rig operating under abrasive wear conditions. This test was performed to assess the assumption of constant wear rate during each oil change period, and to determine the suitability of the wear equation for estimating the material loss during abrasion.

The wear test was conducted by allowing the gearbox to wear in for 100 hours of operation at normal conditions before starting the contaminated lubricant test. The test consisted of 3 oil changes over a total duration of 141 hours, with the gears weighed after each oil change. The contaminant used for the test was silicon dioxide with particle sizes ranging from 8 to 50 microns, at concentrations of 2988, 5058 and 4683 ppm (w/v) for the 3 tests respectively. The raw and derived test results are shown in Table 3. As the concentration of contaminant varied between the oil changes, the gear mass loss was normalised [5], and hence called the specific gear mass loss (SGML).

Table 3. Abrasive wear test results.

| Operating Time (hrs) | Gear Mass (g) | | Change in Gear Mass (g) | | Specific Gear Mass Loss (g/hr•ppm) | | Difference of SGML to Average SGML (%) | |
|---|---|---|---|---|---|---|---|---|
| | Gear | Pinion | Gear | Pinion | Gear | Pinion | Gear | Pinion |
| 0 | 113.3467 | 48.7918 | | | | | | |
| 49.5 | 113.0156 | 48.4967 | 0.3313 | 0.2951 | 2.24E-6 | 2.00E-6 | 0.20 | -2.93 |
| 93.2 | 112.5161 | 48.0330 | 0.4995 | 0.4637 | 2.26E-6 | 2.10E-6 | 1.16 | 2.14 |
| 141.2 | 112.0204 | 47.5673 | 0.4957 | 0.4657 | 2.21E-6 | 2.07E-6 | -1.36 | 0.79 |

The difference between the individual SGML and averages indicate that the specific wear rate of both gears progressed reasonably constant, differing by less than 3%. The unknown entity of this test was comprised of the abrasive wear coefficient and sliding speed, while contaminant concentration can be obtained from the used-oil analysis. This test demonstrates that the wear equation can be used to approximate wear, provided that the wear coefficient and sliding speed can be obtained with sufficient accuracy. As the test procedure was set up for these objectives, true verification of the strategy was not possible. Future tests are planned to test the strategy by using real machine condition data which includes uncertainty in wear coefficients, sliding speed and machine design lifetime.

## 4. SUMMARY

The developed remaining lifetime algorithm consisted of the evaluation and refinement of a wear volume focused approach to component lifetime estimation, taking into account the actual operating conditions of a machine by integration with the condition monitoring program. The milestones of this new development lie in the research into possible lifetime prediction methodologies, the design of the prediction concept including its correlation with condition monitoring data, and the integration with an expert system for condition monitoring. Although this development is still at the research level, the completed algorithm can now be verified by real machine condition data during further development.

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