Wear-oriented state-of-health calculation and classification using operating data

Sandra Rothe, Dirk Söffker

WEAR-ORIENTED STATE-OF-HEATH CALCULATION AND CLASSIFICATION USING OPERATING DATA

Sandra Rothe[1], Dirk Söffker[1]

[1] *Chair of Dynamics and Control, University of Duisburg-Essen,*
Lotharstr. 1, 47057 Duisburg, Germany

sandra.rothe@uni-due.de

ABSTRACT

Reliability and availability of technical complex and safety-critical systems are of increasing importance. The degree of wear as well as the quality of mechatronic systems are significant for the system reliability. To classify the machines state using easy-to-measure signals, two issues are important: filtering and interpretation of the data [1].

Core of this contribution is the development and first application of a simple, easy to use, easy to apply, and easy to handle algorithm to be used directly with industrial data or measurements from technical systems during operation. In this contribution a hydraulically driven machine part sliding over another is used as example. A connection between measured hydraulic data to the degree of wear of the lubricated surface is established to calculate information about the state of a sliding surface.

As experimental data the time behavior of hydraulic pressure data is taken and filtered for better evaluation. To the further generation of suitably defined characteristics, the data are edited and analyzed. The results based on four measurements with two different operating conditions show that the developed approach allows a detailed judgment of wear-oriented state of health as part of a new structural health monitoring system.

KEYWORDS : *SHM principles, classification, monitoring.*

INTRODUCTION

Automated monitoring of wear and classification of the machines state are necessary for reliable state-of-health evaluation, reliable prediction of the actual wear state, to judge the probability of the actual failure behavior as well as the remaining life-time. Known approaches ensuring systems functionality during lifetime are related to Fault Detection and Isolation (FDI) approaches and/or maintenance-related aspects like Condition-Based Maintenance (CBM), Machine monitoring, Structural Health Monitoring (SHM), or related paradigms or philosophies, which are developed during the last 2 decades mainly combining signal- or model-based fault detection or diagnostic approaches. Most of the approaches aim to detect changes in systems occurring due to operation or aging or both leading to changes in measurements. Goal of actual developments is the automatic supervision and maintenance planning to be integrated in operating systems.

One specific task within this context 'supervision of complex mechanical systems' is related to the supervision of wear. Wear results from relative tangential motion between surfaces, is based on material contacts resulting to erosion, deformations, material losses, geometrical sliding surface changes and so on. Within this publication the physical background of these effects will neither be considered and nor interpreted. The focus will be given to the development of signal-based diagnosis and classification routines with respect to the supervision of the state of wear. Here also practical requirements like the transferability to different systems are of interest [2].

Three aspects are relevant:

- processing of the measurement data which are typically problem-specific and to be done in real-time,
- interpretation of the measurement data with respect to the condition of the machine (Health monitoring), and
- establishing the knowledge behind from available measurements and data.

In addition, the approach should be able to evaluate/judge the expected remaining lifetime of the monitored system.

Therefore the used test rig assessing wear is described. After a short presentation of the application example used, the new method developed is explained in detail.

Tribological surfaces are often affected by normal and tangential forces, so the stressed surfaces show severe abrasive wear. Machine elements/parts are often designed for given lifetime assuming known typically given loads. For real simulation of such conditions and to comply the experiments with identical wear conditions, the mechanical and thermal conditions as well as the lubrication should be controlled, so wear test runs has to be realized. Depending on the used material and test parameters, test runs are made with duration of several days up to weeks. The measured values are used to monitor the system and to evaluate the state of the system, the state of wear-related effects, resp. based on load-patterns or stress-equivalent collectives, representative forces can be derived.

A brief sketch of the test rig [1] used within this contribution is shown in Figure 1. The specimens are tangentially conducted, a normal load is applied to shorten the runtime, tangential forces are applied as 'working' forces. Measurements are taken from the hydraulic system (proportional to the friction forces).
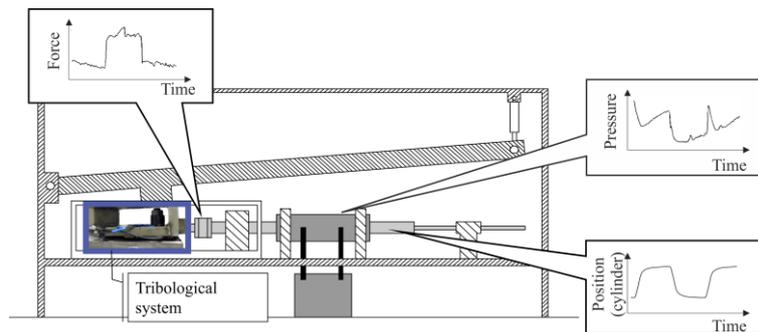

Figure 1: Wear test rig, Chair of Dynamics and Control, U Duisburg-Essen, Germany

Depending on system operation (friction velocity, cycle times (ratio of stress to break times), temperature behavior of the surface, lubricant distribution, etc.) and on the materials used, abrasive sliding wear appears (details, see [3,4]). During the operation period of time the system shows an increased probability to lose its functionality. The following sequence of effects is observed: surface change by crack initiation and growth, lacerated material, and material losses, etc. The surface quality and the degree of wear of the friction partners strongly define the observed systems reliability and functionality. The stress (surface damage, wear debris, surface fatigue) of the friction partners represents a probabilistic process, which depends on the stress history and the current operating parameters [5,6] and can not be described in the sense of a strictly deterministic analysis using known mathematical methods. The automatic monitoring and diagnosis as well as the realization of a wear-oriented control or management of a technical system are the goals of the indented supervision concept to be developed [2]. The key part of the approach introduced here is the definition and establishment of correlations between observed wear and evaluated wear states on the one hand and experimentally measured and suitably filtered signals easy to classify on the other. Significant advantages of the introduced approach should be in relation to known methods like

visual inspection or threshold monitoring stated as follows: no fixed or given models or related structures (in terms of the physical mechanism, damage accumulation, etc.) has to be assumed a priori.

1   DIAGNOSIS-BASED DATA-FILTERING

Due to the motion of the wear surfaces of the test rig, friction appears. Friction related effects are represented implicitly by the force required to move. The applied hydraulic pressure moving the surfaces is proportional to the force and thus also to the friction between the wear surfaces (details, see [3,7]). The following approach is explained briefly in [1]. The wear behavior will be discussed on a different time scale than the signals measured. The time behavior of pressure measurements taken during a load-cycle and filtered for better evaluation has to be known and therefore to be measured all fine. The generation of the characteristic values discussed on the other time scale is explained below. The generation of characteristic values is based on the friction coefficient calculated from the proportional pressure behavior. The considered data are taken from the last 20 seconds of a load-cycle, so the calculated variable is not effected by transient heating effects. For one load-cycle the measured signal (of 20 seconds) is considered using a sliding window technique, in which the arithmetic mean of a window including 1 second of measured signals is calculated. From the arithmetic mean of all means from each window the characteristic value for one load-cycle is calculated. For one measurement (here denoted as the set up Z15), the time-behavior of the pressure equivalent characteristic value is shown in Figure 2 (first row, first column).

The measured hydraulic pressure signals are filtered to calculate the characteristic values described before. To further generation of characteristics, the absolute values of the difference of the individual characteristic values are calculated. Divided by the time-difference between the individual characteristic values damage increments are computed. After each load-cycle all damage increments calculated before are accumulated (AS) and plotted as a function of time (see Figure 2 (second row, first column)). The development of AS shows changes in gradient with increasing time.

The gradient of the AS-curve is smoothed by centered moving average. A specific number of values before and after the actual value is used to calculate the mean value. In Figure 2 (third row, first column) the centered moving average of AS gradient is plotted logarithmical.

2   THRESHOLD-BASED CLASSIFICATION

The gradient can be divided into areas representing the different wear-related states of the sliding surface (according to [8]). The curve shows that the surface condition generates temporarily very large friction-related characteristics. Here it is assumed that four significant behaviors of the gradient of AS describing the surface condition exist as displayed in Figure 2 (third row, first column):

- State 1: stable and error free operation (below green line),
- State 2: stable with small changes of surface condition (between yellow and green line),
- State 3: acceptable changes of surface condition (between red and yellow line), and
- State 4: significant changes of surface condition (above red line).

If there are no measurement data available (e.g. during stop of the experiment), the corresponding time is denoted as state 0. The threshold values are chosen experimentally from previous measurements. In Figure 2 (last row, first column) the discretized machine state for every load-cycle is shown.

3   RESULTS OF THE APPLICATION

In this contribution four measurements with two different operating conditions (change of lubrication interval and surface material) are analyzed.
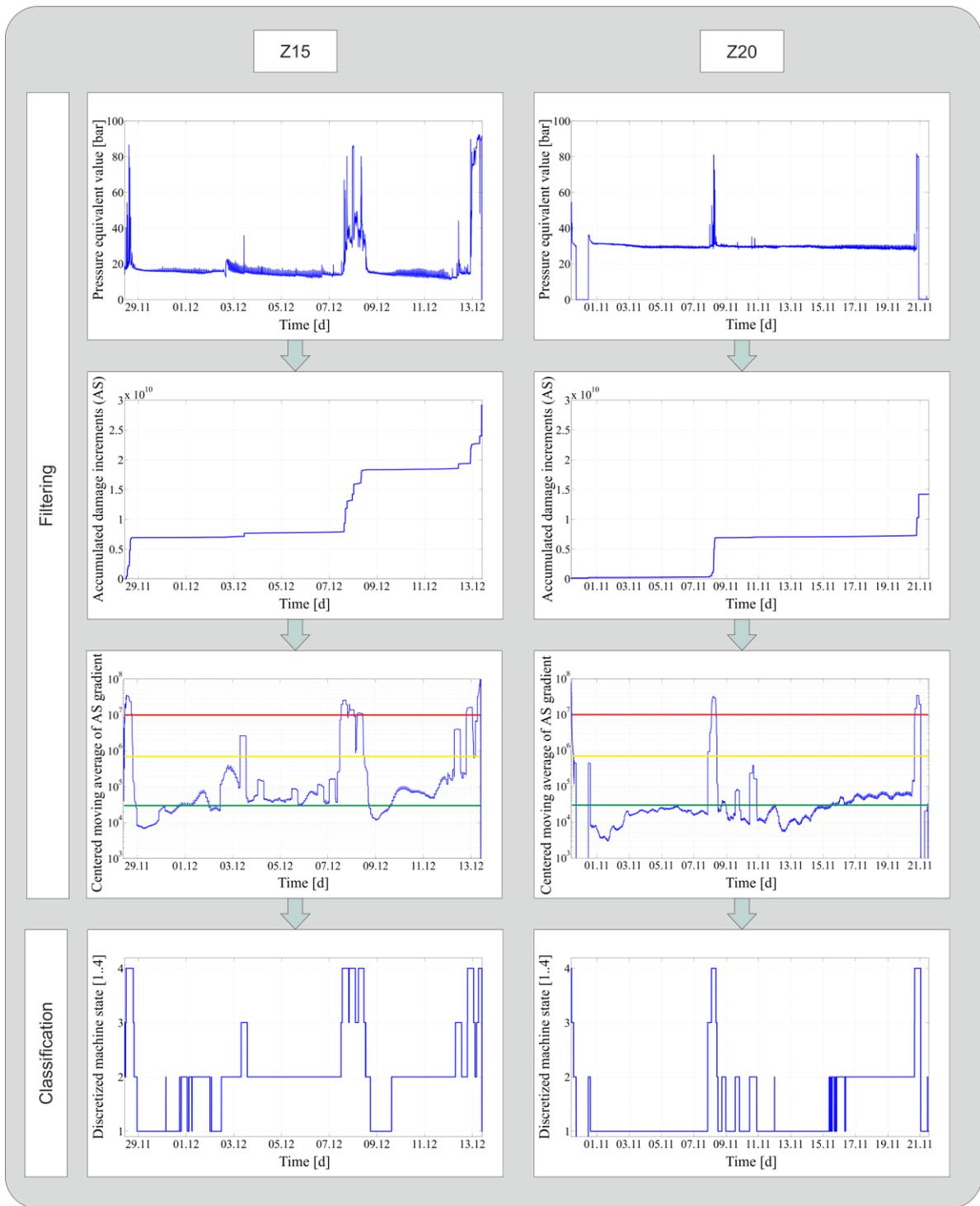
Figure 2: Comparison of two measurements (Z15 and Z20) with same operating conditions

In Figure 2 measurements from the two set ups Z15 and Z20 are shown. Here the same conditions are applied. The filtering and classification methods mentioned above are used to classify the machine state. Same values of threshold can be used, because after filtering the values of the centered moving average of AS gradient are in the same range. It can be seen, that in principle the classified machine states have a similar structure. Phases of run in (at the beginning of the

measurement), the interim phase of permanent wear and the final destruction phase exist. Constant wear progression phases classify periods of time of steady state behavior. Occasional phases with significant changes of the surface condition (State 4) appear, but the system returns to a stable and error free operation (State 1).
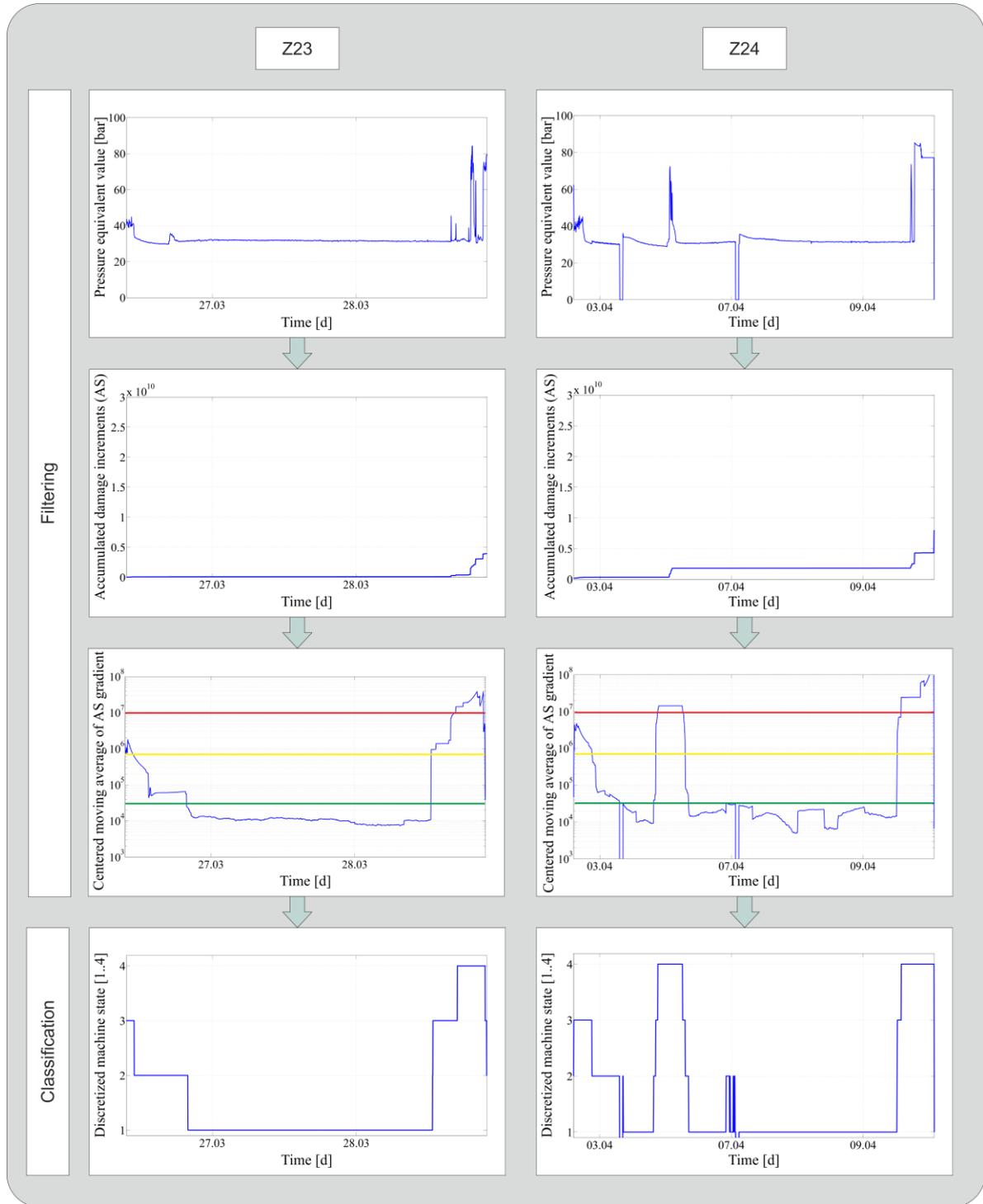

Figure 3: Comparison of two measurements (Z23 and Z24) with same operating conditions

The results for another set of comparable measurements (set ups Z23 and Z24 as shown in Figure 3), are obtained applying different operating conditions (no lubrication after the run-in phase). The threshold values are still the same.

The three phases (run-in phase, interim phase of permanent wear and the final destruction phase) also exist in these set ups.

The durations of the set ups Z23 and Z24 are less than the durations of the set ups with lubrication Z15 and Z20. From Figure 2 in comparison with Figure 3 it can be seen that more lubrication (Z15/Z20) will lead to more changes of pressure behavior and therefore of machine state during the phase of permanent wear (Figure 2 (first and last row)). Lubrication changes the surface conditions, so the life time exceeds.

Another run-in phase with less influence on pressure behavior can be seen after a stop of the experiment (see Figure 2 (first row, second column) and Figure 3 (first row, second column)).

From the experimental results it becomes clear, that the wear process runs individually, but can be compared from a structural point of view by introducing different phases obviously identical to the development of the wear processes. The parameters/features for suitable distinction have to be discussed and detailed in future work.

CONCLUSION

The presented new approach based on the use of easy to get operating data is simple in various aspects: easy to have measurements are integrated into operations management. The modules can be implemented to the decision logic modules for condition assessment. From the application it can be shown that the application complexity for users is low. It also shows a low complexity for developers. The approach has a strong real-time capability. However, the mechanisms may not lead to directly identifiable information. By classification of the machine state operating conditions like interval of lubrication can be changed during the experiment depending on the state, so that the changes of surface conditions can be reduced and the life-time of the machine can be extended. For realization, additional measurements have to be done.

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