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USING OF KALMAN FILTER AS A PROGNOSTIC TOOL FOR TRIBOLOGY PROCESSES

Ivan Mačužić[1], **Petar Todorović**[1], **Marko Đapan**[1], **Milan Radenković**[1], **Branislav Jeremić**[1]
[1]Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia,
ivanm@kg.ac.rs, petar@kg.ac.rs, djapan@kg.ac.rs, radenkovic@kg.ac.rs, bane@kg.ac.rs

Abstract: *The paper consider possibilities for performing of prognostic procedure for tribology processes in hydraulic equipment using advanced mathematical tool called Kalman filter. It is an algorithm that uses a series of measurements observed over time, containing noise and other inaccuracies, and produces estimates of monitored parameter that tend to be more precise than those based on a single measurement alone. Kalman filter operates recursively on streams of noisy input data to produce a statistically optimal estimate of the underlying system state.This type of procedure could be used for prognostic of state of chosen parameter of tribology system with significantly accuracy. Efficiency of Kalman filter were tested on experimental results of hydraulic oil contamination monitoring performed in laboratory conditions.*

Keywords: *Kalman filter, prognostic, tribology processes, hydraulic equipment*

1. INTRODUCTION

Prognostics is a set of activities aimed at assessing the remaining time to failure for a particular technical system or risk of presence or occurrence of one or more failure modes in the future. Prognostics efficiency can be quite satisfactory for the failure modes that have repeating time characteristics, followed by progressive degradation of key exploitation characteristics [1].

In cases of failure modes with random and unexpected events, prognostic is a very difficult task with uncertain results.

Prognostic process could be based on the model, or on the measurement results. Prognostic based on the measurement results includes the use of various mathematical tools for monitoring and predicting, such as for example Kalman filter and its simplified version known as alpha-beta-gamma filter [2].

2. KALMAN FILTER

Signal filtering, and extracting the useful signal from noise is a traditional problem in science and technology. Significant number of models and algorithms was proposed and developed for solving of this problem. In case when signal and noise spectra lies in different frequency bands, their separation can be made with appropriate band filters.

Another problem arises when the spectra of the signal and noise overlap and then statistical methods for the assessment and evaluation of the signal should be used to extract the signal. In such circumstances it is not possible to obtain an accurate absolute value of the signal, and all the methods of filtration are made only to minimize interference.

The first such analog signals filter suggested by Norbet Winer in 1940. using the method of least squares. New stage in the development of the theory of filtration began Rudolf Emil Kalman in 1960., with publication of his capital work, "A New Approach to Linear Filtering and Prediction Problems" in which it was first introduced method will become known in science as the Kalman filter [3].

The Kalman filter is a mathematical tool that can be used to assess the value of variables in different forms of real situation. Mathematically speaking Kalman filter evaluates the condition of linear systems. It is a statistical technique that combines the statistical nature of system faults with knowledge of the system dynamics, and those matrixes describe the state of the system and their evaluation.

The significance of this method is that, on the one hand it gives excellent results in practice, while, on the other side, is theoretically attractive since it has been demonstrated that all of the filters that are applied precisely this variation achieved by minimizing the error estimates [4], which is often also called the optimal filter.

Application of Kalman filter was recently, in addition to traditional applications related to signal processing, automatic control systems and processes, and the projection of the trajectory and ballistic missiles, and a significant number of new areas such as medicine systems, global positioning satellite (GPS) navigation, computer vision, economics, and so on.

In order to use the Kalman filter to remove noise from the signal, system, or process that is considered to be such that it can be approximated as linear and present. For nonlinear systems, which can't be present or approximated as linear, the so-called. Extended Kalman filter is developed as an extension of the theory of linear Kalman filter to nonlinear systems [4].

Linear systems are those that can be represented using the following two equations. The first is the equation of state:

$$x_{k+1} = Ax_k + Bu_k + w_k \quad (1)$$

the other is the output of the system of equations:

$$y_k = Cx_k + z_k(1) \quad (2)$$

These equations are:
A - matrix that shows the relationship of current and previous step, *B* - matrix connections inputs and the current state, *C* - matrix state and do the measurements, *k* - time index, *x* - variable that indicates the state of the system, in - known input the system, *y* - the output of the system being measured, and *w* and *z* are noises where *w* is called process noise and *z* - measurement noise.

Each of these values is generally a vector that contains more than one element. Vector *x* contains all the information about the current state of the system but we are not able to measure directly. Therefore, we measure the value of the vector *y* which is a function of the vector *x* with the addition of measurement noise *z*. This means that over the measured values of the vector *y* can assess the state system described by vector *x*.

Introduced the assumption that the average value of the process noise *w* and the measurement noise *z* is zero during a time interval and that there is no correlation between them, and that the two forests have approximately a normal distribution with covariance *Sw* and *Sz*. Based on the above can be derived equations for the Kalman filter [4]:

$$K_k = AP_kC^T(CP_kC^T + S_z)^{-1} \quad (3)$$

$$\hat{x}_{k+1} = (A\hat{x}_k + Bu_k) + K_k(y_{k+1} - C\hat{x}_k) \quad (4)$$

$$P_{k+1} = AP_kA^T + S_w - AP_kC^TS_z{}^{-1}CP_kA^T \quad (5)$$

Each of the three defined equations of Kalman filter includes a series of operations with matrices where the index *T* represent matrix transposition and index *-1* represent matrix inversion. Matrix *K* is called the Kalman gain and the matrix *R* estimation of error covariance.

Obviously, the Kalman filter works recursively and takes only the value of the system state at the previous time point to generate assessment following conditions (not required the entire history of the state).

The Kalman filter can be used in different ways to handle real signals where the results are quite different nature and use. When the filter is used to estimate the previous state of the known history of the system (measured values) is obtained by eliminating the possibility of measuring noise in order to level the curve that defines the state of the system changes over time in the past. If we estimate the current state of the system is the result of filtering the measured signal [4], [5].

The filter can be used for the prediction of the system in the near future if the state of the system in estimated time is moved to next time interval in advance. This means that the estimated state and the actual state were time-shifted by an interval so in accordance with the assessment of the situation for the time moment *k+1* conducted on the basis of estimated values of *x* from time to time and measured values at the time point k + 1. This is possible because the movement of the estimated state for a time interval of pre-practice leads to temporal overlap of the estimated state *x* from *k+1* timing and the real state of *x* from *k* time. Practically on the basis of previous estimates and errors in the actual situation new value is evaluated for the next time point.

One of the great advantages of Kalman filter is its feature that it is not necessary to carry out detailed modelling of system which condition is estimated. The reason for this lies in the recursivity principle of Kalman filter and the periodic repetition of the process of assessment and correction, and built-in tendency to corrects and minimize error from step to step. This feature opens the door to a wide use in solving various technical problems since the generation of an accurate model of the real system is a very demanding and complex task [5].

3. KALMAN FILTER APPLICATION FOR PROGNOSTIC OF TRIBOLOGY PROCESSES IN HYDRAULIC

The essence of the idea for the application of Kalman filter for forecasting and prognostic of tribology processes lies in the fact that it is a tool that is least dependent on the accuracy of the model of tribology system that is considered. The procedure involves projections to prognostic in mathematical modelling of the behaviour of tribology parameters in time, which severely limits the application of other, model-based, prognostic tools, since they are directly dependent on the characteristics of the model for a specific system.

On the other hand, Kalman filter will provide very useful results even for very approximate models and also for some standard, general models of system behaviour in time (that do not even have direct link with the observed system),.

It is clear that the Kalman filter works only at discrete points in time, and its use is related to digital signal processing. Complex math, matrix transformations and calculations, represent an easy task for modern computers and processors to the stabile and to mobile devices, which also allowed the installation of Kalman filters in numerous portable monitoring devices.

As an example of application of Kalman filter for prognostic of tribology processes, trending of contamination level in hydraulic equipment will be presented.

Method of hydraulic oil contamination values prognostic (based on ISO4406 contamination level code) using Kalman filter is shown on Figure 1. From 200 measured points, that define the values of contamination level, for particles of defined size, 9 points was allocated (8 is shown from T1 to T8).

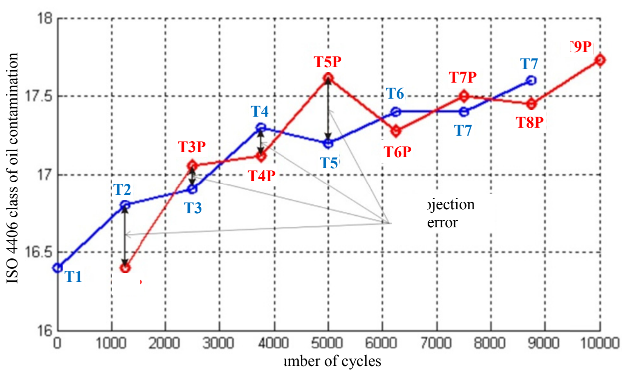

Figure 1. Kalman filter prognostic process

In this case, those are equidistant points, although, in general, do not have to be. Based on the value of the first point of T1 and set parameters of Kalman filter define the value of the first projected point in the future (T2P). Since there is no additional information other than the value of T1, Kalman filter defines point T2P so that its value is the same as the value of the point T1. This is the initial assumption that nothing will change.

At the time of obtaining the measured values of other points - T2, the projection error is calculated as the difference in point values T2 and T2P. On the basis of the projection error values and measured values point T2, Kalman filter performs the projection of the value of the third point T3P. Then a new measured value of contamination T3 is received and new projection error is calculated and the cycle is repeated.

Practically the value of each new projected point is function of the previous measured value and projection errors in the previous point.

At Figure 2, diagram obtained by the projection of contamination using a Kalman filter for the curve related to the measured contamination of hydraulic oil is shown, together with diagram of error projections. Prognostic process is conducted for 40 points, which define the value of contamination, in first attempt and 10 points in second one.

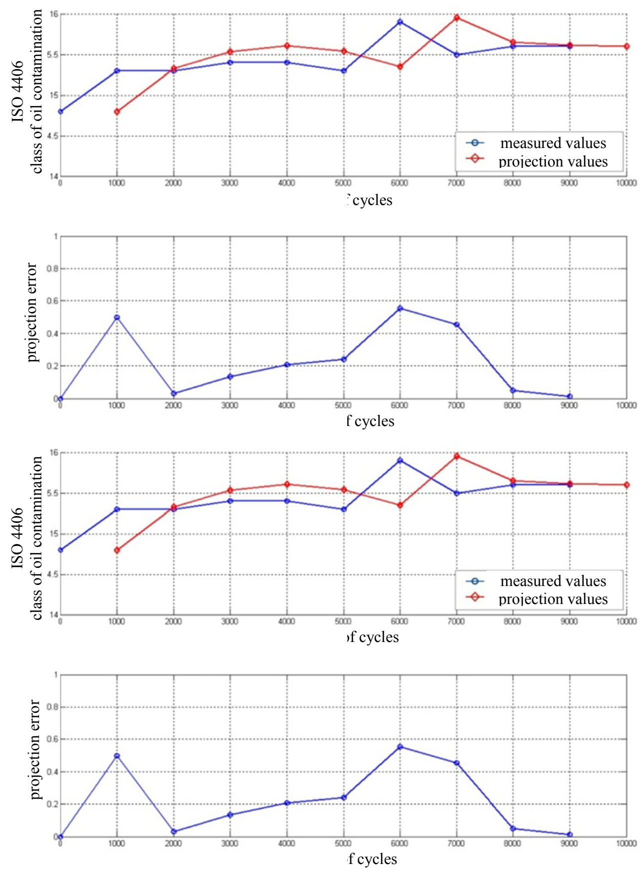

Figure 2. Kalman filter prognostic and projection error

At Figure 3. diagrams obtained by the projection of contamination using the Kalman filter for oil sample from the test with the external addition of contamination in the contact zone is shown.

Total of 3 diagrams are shown in Figure 3. refers to variants of Kalman filters with different values influence of the measurement noise (from lower to higher)

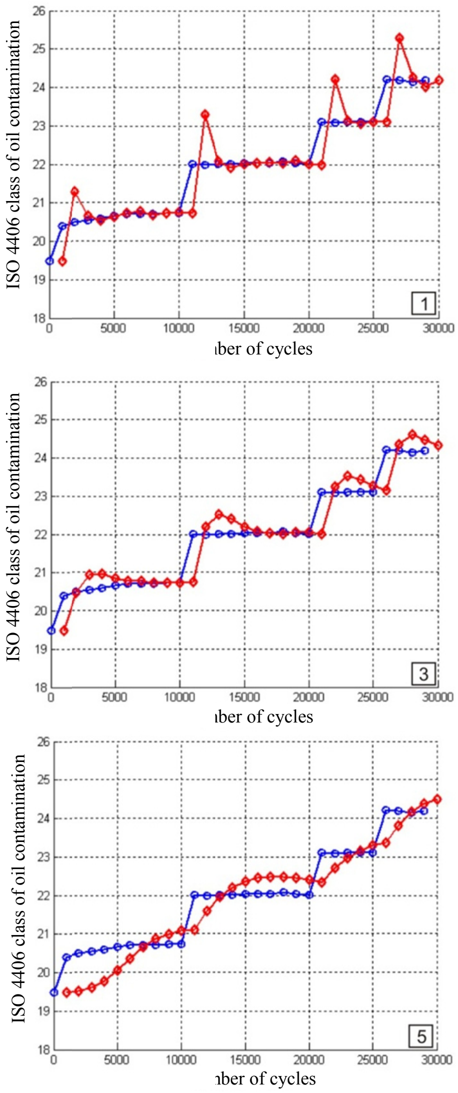

Figure 3. Kalman filter prognostic with step-change in contamination for different values of measurement noise

4. CONCLUSION

Based on shown results some general conclusions about process of prognostic using the Kalman filter could be defined:

- The examples of practical application of prognostic using Kalman filter obtained very good results in tracking of real measured values with acceptable projection error in case of measured diagrams without sudden and significant changes of contamination value.
- The biggest mistake of projection, as a rule, is right at the beginning at first projected point.
- Variations in the values of the measured signal and noise measurement have a direct impact on the accuracy of the prognostic.
- The influence of the measurement noise on the result of the projection can be adjusted using the definition of the value of the corresponding parameter in the Kalman filter equations. Increasing the value of this parameter indicates the presence of more intensive measuring noise and vice versa.
- In the case of a sharp and abrupt prognostic using a Kalman filter have visible and the expected delay in the response to change. It is clear that there is no method of forecasting, which can predict the occurrence of sudden, unexpected and abrupt changes in the values followed by the diagnostic parameter. In any case, these phenomena point to the serious irregularities and problems in the system and certainly represent an alarm signal.
- The great advantage of using Kalman filter lies in its full independence and insensitivity to the shape and characteristics of the measured contamination trend charts.

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