

# From measurement collection to remaining useful life estimation: defining a diagnostic-prognostic frame for optimal maintenance scheduling of choke valves undergoing erosion

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## ABSTRACT

Condition Based Maintenance (CBM) aims at regulating maintenance scheduling based on data analyses and system condition monitoring. Clear advantages of optimizing maintenance scheduling include relevant cost savings and improved safety and plant availability. A critical aspect is the integration of CBM strategies with condition monitoring technologies for handling a wide range of information sources and eventually making optimal decisions on when and what to repair. In this work, a practical case study concerning maintenance of choke valves in offshore oil platforms has been investigated. Choke valves used in offshore oil platforms undergo erosion caused by the sand grains transported by the oil-water-gas mixture extracted from the well. Erosion is a critical problem which can affect the correct functioning of the valves, result in revenue losses and cause environmental hazards. In this respect, this work proposes a diagnostic-prognostic scheme for assessing the actual health state of a choke valve and eventually estimating its Remaining Useful Life (RUL). In particular, the focus has been on the identification of those parameters which contribute to the actual erosion of the choke valve, the development of a model-based approach for calculating a reliable indicator of the choke valve health state, the actual estimation of the choke RUL based on that indicator using statistical approaches and, finally, the investigation of methods to reduce the uncertainty of the RUL estimation by adding

highly meaningful knowledge on the erosion state of the choke valve\*.

## 1. INTRODUCTION

In oil and gas industries, choke valves are normally located on top of each well and are used to balance the pressure on several wells into a common manifold to control oil, gas and water flow rates and protect the equipment from unusual pressure fluctuations. Figure 1 sketches a choke valve.

The throttle mechanism consists of two circular disks, each with a pair of circular openings to create variable flow areas. One of the disks is fixed in the valve body, whereas the other is rotated either by manual operation or by actuator, to vary or close the opening. For large pressure drops, the well stream containing gas, liquid and sand particles can reach 400-500 m/s and produce heavy metal loss mainly due to solids, liquid droplets, cavitation and combined mechanisms of erosion-corrosion, resulting in choke lifetimes of less than a year. Erosion management is vital to avoid failures that may result in loss of containment, production being held back, and increased maintenance costs. Moreover, several chokes are located subsea, where the replacement cost is high (Andrews *et al.*, 2005; Bringedal *et al.*, 2010; Haugen *et al.*, 1995; Hovda and Andrews, 2007; Hovda and Lejon, 2010; Jarrel *et al.*, 2004; Ngkleberg, and Sontvedt, 1995; Wallace *et al.*, 2004).

For these reasons, attention has focused on the maintenance of choke valves. Currently, fixed maintenance is the most common way to manage choke replacement. A

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more effective way to handle maintenance is to base it on indications of the actual condition (i.e. health state) of the choke valve and possibly on the estimations of its remaining useful life (RUL) (Gola and Nystad, 2011; Kiddy, 2003; Nystad *et al.*, 2010; van Noortwijk and Pandey, 2003).

In general, condition-based maintenance (CBM) approaches rely on data analysis and condition monitoring systems. In fact, the measurements of those parameters considered relevant to assess the health state of a component are first processed by condition monitoring systems which return the diagnostic indication of the current health state. This indication can be then used within prognostic systems to eventually estimate the remaining useful life of the component (Fig. 2).

The integration of condition monitoring systems with CBM strategies is critical for handling a wide range of information sources and providing a reliable indication upon which optimal decisions can be made on when and what to repair.

In this work, the diagnostic-prognostic scheme sketched above is applied to a real case study of choke valve erosion. In this respect, an empirical, model-based condition monitoring system is developed to process the collected measurements in order to give a reliable indication of the erosion state of the choke. A statistical prognostics system based on the gamma process is then used for the estimation of the remaining useful life of the choke.

The work is organized as follows: Section 2 describes the parameters used to assess the choke valve erosion state; Section 3 reports the case study under analysis. Section 4 illustrates the diagnostic-prognostic scheme hereby proposed to assess the choke erosion state and to estimate its remaining useful life. Conclusions are drawn in the last Section.

## 2. CHOKE VALVE EROSION ASSESSMENT

In the generic choke valve fluid dynamic model, the total flow  $w$  through the choke is proportional to the pressure drop  $\Delta p$  through the choke:

$$w = C_V \sqrt{\frac{\Delta p}{\rho}} \quad (1)$$

where  $\rho$  is the average mixture density and  $C_V$  is called valve flow coefficient.  $C_V$  is related to the effective flow cross-section of the valve and is proportional to the choke opening according to a function depending on the type of choke valve and given by the valve constructors, i.e. for a given choke opening,  $C_V$  is expected to be constant (Metso Automation, 2005).

When erosion occurs, a gradual increase of the valve area available for flow transit is observed even at constant pressure drop. Such phenomenon is therefore related to an

abnormal increase of the valve flow coefficient with respect to its expected theoretical value, hereby denoted as  $C_V^{th}$ .

For this reason, for a given choke opening the difference  $\delta_{C_V}$  between the actual value of the valve flow coefficient, hereby simply denoted as  $C_V$ , and its theoretical value  $C_V^{th}$  is retained as an indication of the choke erosion. The difference  $\delta_{C_V} = C_V - C_V^{th}$  is expected to monotonically increase throughout the choke life since it should reflect the physical behaviour of the erosion process. When  $\delta_{C_V}$  eventually reaches a pre-defined failure threshold, the choke must be replaced.

The actual valve flow coefficient  $C_V$  cannot be directly measured, but it can be calculated from the following analytical expression which accounts for the physical parameters involved in the process:

$$C_V = \frac{w_o + w_w + w_g}{N_6 F_p \sqrt{p_{in} - p_{out}}} \sqrt{\frac{f_o}{\rho_o} + \frac{f_w}{\rho_w} + \frac{f_g}{\rho_g} J^2} \quad (2)$$

where  $p_{in}$  and  $p_{out}$  are the pressures upstream and downstream of the choke,  $w_o$ ,  $w_w$  and  $w_g$  are the flow rates of oil, water and gas,  $f_o$ ,  $f_w$  and  $f_g$  the corresponding fractions with respect to the total flow rate and  $\rho_o$ ,  $\rho_w$ ,  $\rho_g$  and the corresponding densities,  $J$  is the gas expansion factor,  $F_p$  is the piping geometry factor and  $N_6$  is a constant equal to 27.3 (Andrews *et al.*, 2005; Gola and Nystad, 2011; Hovda and Andrews, 2007; Metso Automation, 2005; Nystad *et al.*, 2010).

## 3. CHOKE VALVE EROSION: THE CASE STUDY

A case study on a choke valve located top side on the Norwegian continental shelf is here considered.

Measurements and calculations related to the physical parameters involved in the process are available as daily values. In particular, the pressures upstream and downstream of the choke are directly measured, whereas oil, gas and water flow rates are calculated based on the daily production rates of other wells of the same field. Pressure measurements are considered reliable since they are directly related to the well under analysis, whereas the calculations of oil, gas and water flow rates expected from that well might not be realistic and therefore might not reflect the actual physical composition of the extracted mixture. In addition to the daily measurements and calculations, seven well tests are carried out throughout the valve life at regular intervals, during which oil, gas and water flow rates are accurately measured using a multi-phase fluid separator. The valve choke opening is also provided as a parameter.

Since oil, gas and water flow rates are used to compute the actual  $C_V$  (Eq. 2), inaccuracies in their calculation might negatively affect the  $C_V$  calculation itself and thus the quality of the erosion indication  $\delta_{C_V}$ .

Figures 3 and 4 illustrate the parameters used to compute the actual  $C_V$  and the resulting erosion indication  $\delta_{C_V}$ , respectively.

The mismatch between the values of oil, water and gas flow rates daily calculated accounting for the other wells and the values of the same three parameters measured during the well tests is evident in the bottom graphs in Figure 3. Notice that there is instead no mismatch for the pressure drop and, obviously, for the choke opening indication (top graphs in Fig. 3).

As a consequence of the inaccurate daily calculations of oil, water and gas flow rates, the daily erosion indication  $\delta_{C_V}$  (black line in Fig. 4) results non-monotonic and very noisy, generally showing an unphysical behaviour. On the other hand, when  $\delta_{C_V}$  is computed using the well test measurements of oil, water and gas flow rates, its behaviour results monotonic and provide a reliable information on the physical erosion process.

Nevertheless, a diagnostic assessment on the erosion state of the valve and a prognostic estimation of its remaining useful life cannot be made based on the daily erosion indications. In the next Section, an empirical model-based approach is used to produce a reliable daily calculation of the erosion state which is then fed to a prognostic system for estimating the choke remaining useful life.

#### 4. IMPROVING THE EROSION STATE CALCULATION FOR ASSESSING THE CHOKE REMAINING USEFUL LIFE

A method developed at the Norwegian Institute for Energy Technology and called Virtual Sensor is here used (PCT/NO2008/00293, 2008). Virtual Sensor is an empirical method based on the use of an ensemble of feed-forward Artificial Neural Networks (ANNs). In general, given a number of input parameters correlated to a quantity of interest, the Virtual Sensor aims at providing a reliable estimate of that quantity.

In general, a subset of the available data (in the format input-parameters/output-target) is used to train the ANN models, i.e. to tune its parameters, with the goal of learning the ANN to estimate the output target. Once the model is trained, it can be used on-line by providing a stream of input measurements in order to obtain an estimate of the (unknown) output.

Virtual Sensor exploits the concepts of ensemble modelling which bear the advantages of ensuring high accuracy and robustness of the estimation without the need of developing one single optimal model. Critical aspects of ensemble modelling are the diversity of the individual

models, hereby ensured by randomizing the training initial conditions of the ANNs, and the aggregation of the outcomes of the individual models, hereby performed by retaining the median of the individual estimates.

In this work, Virtual Sensor is used to provide a reliable estimation of the actual  $C_V$  based on the set of available input parameters, namely the pressure drop, the choke opening and the oil, water and gas flow rates. Given the limited amount of available data, the Virtual Sensor has been trained by using as output target a  $C_V$  obtained by the linear interpolation of the  $C_V$  values calculated with the well test measurements. Figure 5 shows the erosion indication  $\delta_{C_V}$  obtained with the Virtual Sensor daily estimations of  $C_V$  compared with the one obtained using the Equation (2). Despite the erosion indication obtained with the Virtual Sensor is still not completely monotonic, the improvement with respect to the one obtained using Equation (2) is evident.

The erosion indication obtained with the Virtual Sensor conveys a more physically reliable indication of the erosion state of the choke and can be used both within a diagnostic frame to assess the valve performance in the present and within a prognostic system for predicting the temporal evolution of the erosion, eventually estimating when the erosion will cross the failure threshold and the valve needs to be replaced.

To this aim, a statistical approach based on gamma process (van Noortwijk and Pandey, 2003) is here used. Gamma process is a statistical analysis based on Markovian principles and gamma probabilistic distribution.

In a generic prognostic problem, the gamma process exploits the knowledge embedded in the health state indications to calculate the parameters of the temporal evolution of such indication. According to the gamma process, the increments of the health indications are gamma-distributed and can therefore be only positive representing a monotonic quantity. This makes the approach suitable to model the choke valve erosion process which is naturally monotonic.

The expected temporal trend of the health indicator  $h$  at time  $t$  (i.e. the expected value of the gamma distribution at time  $t$ ) is  $h(t) = \frac{a}{c} t^b$ , where  $b$  is the parameter which regulates the concavity/convexity of the trend shape and  $a$  and  $c$  determine the spread of the gamma probability distribution.

Given a failure threshold for the health indicator, the gamma process calculates the conditional probability that the component fails at time  $t > T$  given that it has survived up to time  $T$  (hereby called time-based approach). The quality of this additional information is critical to define the failure time probability distribution.

In this work, a different approach (hereby called state-based approach) has been adopted which accounts for the knowledge of the actual valve health state. In this view, the gamma process calculates the conditional probability that the component fails at time  $t > T$  given the knowledge of its current health state is  $h(T) = H$ . This approach exploits information of noticeably higher quality, given that a pre-defined list of discrete health states for a component is available based on expert analysis (Gola and Nystad, 2011; Kiddy, 2003).

Another critical issue is the calculation of the parameters of the expected gamma function. In particular, the accurate determination of  $b$  is fundamental to obtain meaningful values of the remaining useful life.

Different methods can be used to calculate  $b$ . In this work,  $b$  is determined by a weighted least-square optimization. Given a time series of health state calculations  $b(t)$ ,  $t = 1, \dots, T$ ,  $b$  at current time  $T$  is determined by the least-square method using the log-transformed expression for  $h(t)$ , i.e.  $\ln(h(t)) = \ln\left(\frac{a}{c}\right) + b \ln(t)$ . Parameter  $b$  is therefore the angular coefficient of the straight line which best interpolates the log-transformed health state calculations up to time  $T$  given the condition that the interpolation passes by the last available health state calculation, i.e.  $\ln(h(T)) = \ln\left(\frac{a}{c}\right) + b \ln(T)$ .

The so-called weighted least-square optimization amounts to improving the calculation of  $b$  by assigning more importance to the most recent health state calculations which are conjectured to be the most informative. In practice, this is done by artificially adding to the time series of the health state calculations a number  $K$  of replicates of the last  $N$  health state calculations, i.e.  $h(t)$ ,  $t = T - N, \dots, T$ . This way of proceeding forces the least-square optimization to better approximate those health state calculations considered most relevant to determine the shape of the gamma function. Once the value of  $b$  is set, parameters  $a$  and  $c$  can be analytically determined using the method of moments (van Noortwijk and Pandey, 2003).

In this case study, measurements corresponding to 305 operational days are available. Approximately 235 operational days of measurements are collected and processed with the Virtual Sensor to produce reliable erosion state indications  $\delta_{C_v}$  before the gamma process is devised to estimate the choke remaining useful life. This amount of measurements is conjectured to be sufficient to achieve reliable calculations of parameters  $a$ ,  $b$  and  $c$ . The weighted least-square optimization is done by considering  $K = 1000$  replicates of the last  $N = 50$  erosion state indications. This augmented virtual measurement set forces the gamma process to provide the best fit, in terms of

least-square error, for the last 50 collected measurements, which indeed bear the most recent and therefore valuable information on the valve erosion state.

The estimation of the RUL and its uncertainty is then carried out every operational day until the choke is actually replaced. The failure threshold for the erosion indicator  $\delta_{C_v}$  is set equal to 16. Since the gamma process requires a monotonic data series, the erosion indicator  $\delta_{C_v}$  is first filtered with a combination of moving average and moving maxima.

Results of the remaining useful life estimation are shown in Figure 6 and compared to those obtained when the  $b$  parameter is set constant and equal to 2.2 which is the value that best fits the last 50 available erosion state indications  $\delta_{C_v}$  in terms of least-square error.

The slowly increasing values calculated for the erosion indicator  $\delta_{C_v}$  up to 273 operational days (Fig. 5) lead to having values of  $b$  with the weighted least-square optimization smaller than 1. As a consequence, the resulting convex shape of the expected gamma function hits the failure threshold at considerably large times, thus returning an overestimated value of the choke remaining useful life.

On the other hand, when values of the erosion indicator  $\delta_{C_v}$  show a sharp increase towards the end of the choke life, the weighted least-square optimization allows to quickly update the value of  $b$  with the effect of obtaining a more precise estimation of the remaining useful life, which, after 290 operational days is comparable to that obtained by fixing  $b$  equal to the value which best fits the last 50 measurements.

## 5. CONCLUSIONS

In this paper, a practical case study concerning erosion in choke valves used in oil industries has been analysed with the aim of defining a diagnostic-prognostic frame for optimizing maintenance scheduling of such components.

Two objectives have been identified: 1) the development of a condition monitoring system capable of providing reliable calculations of the erosion state based on collected measurements of physical parameters related to the choke erosion and 2) the development of a prognostic system to accurately estimate the remaining useful life of the choke.

An empirical, model-based approach has been used to fulfil the diagnostic objective of providing reliable calculations of the erosion state, whereas a statistical method based on the gamma probability distribution has been adopted to reach the prognostic goal of accurately estimating the remaining useful life of the choke.

Although the results obtained so far are encouraging with respect to the goal of defining a diagnostic-prognostic frame for optimizing maintenance scheduling of choke valves, a strong limitation of the proposed procedure has

been envisioned in the amount and the quality of the available data. In fact, it is evident that having data corresponding to one single valve considerably affect the general applicability of the approach which has not been yet demonstrated. With a larger amount of data related to many similar valves one could in fact perform a more consistent training of the Virtual Sensor and eventually define an optimal value for the shape-parameter of the gamma function. In this respect, more measurements are currently collected and further analysis and research is planned.

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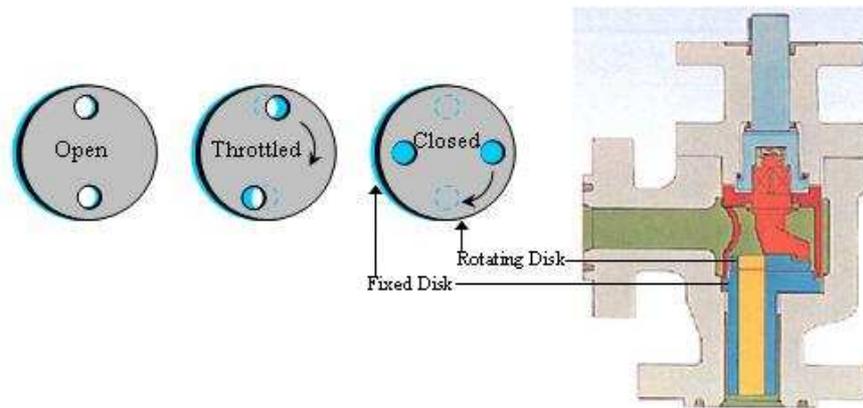


Figure 1: Typical choke valve of rotating disk type: by rotating the disk the flow will be throttled (picture taken from [www.vonkchokes.nl](http://www.vonkchokes.nl))

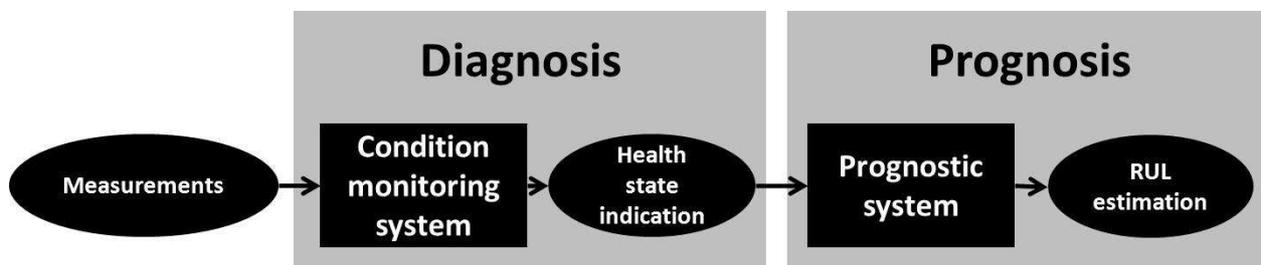


Figure 2. General diagnostic-prognostic frame.

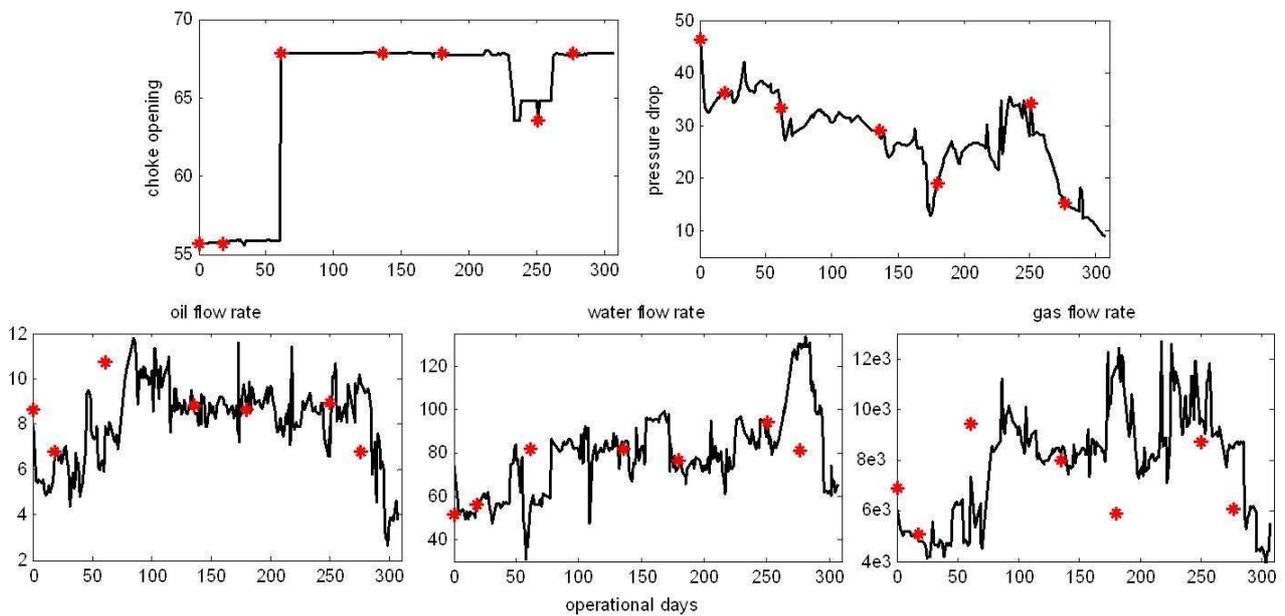


Figure 3. Choke opening and pressure drop (top graphs) and oil, water and gas flow rates (bottom graphs) during daily measurements (black line) and well tests (red stars).

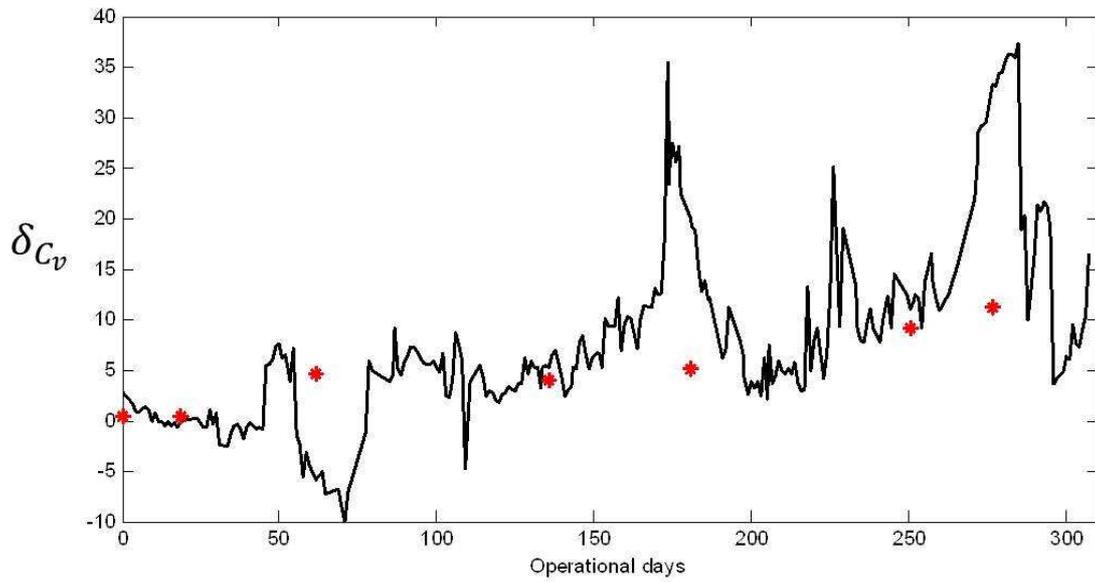


Figure 4. Erosion indication ( $\delta_{C_V}$ ) obtained with  $C_V$  calculations based on daily measurements and calculations (black line) and computed using the measurements of the well tests (red stars).

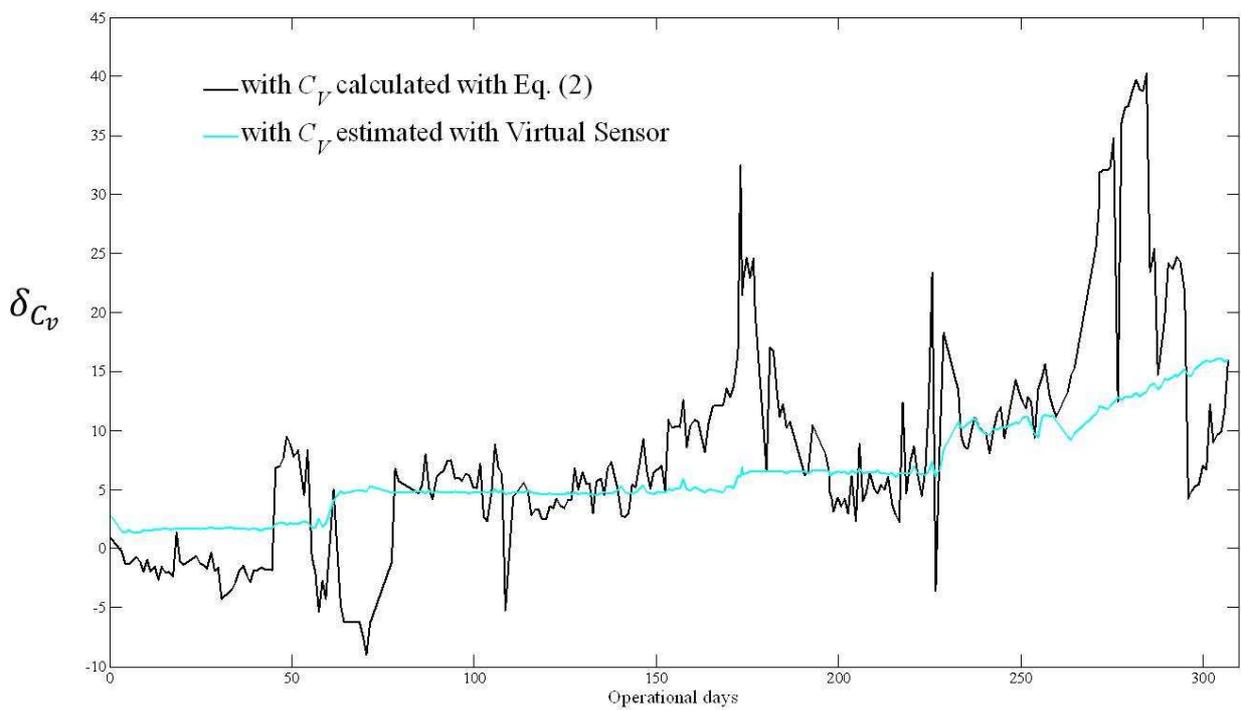


Figure 5. Erosion indication ( $\delta_{C_V}$ ) obtained with  $C_V$  calculated with Eq. (2) (black line) and with the Virtual Sensor (light blue line).

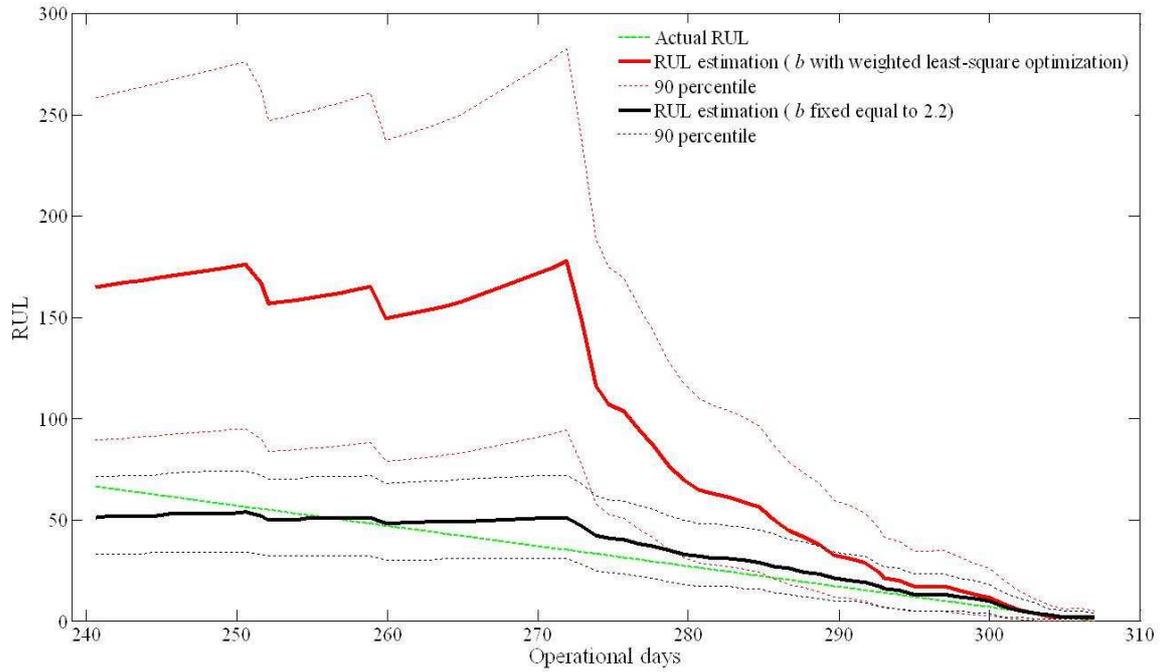


Figure 6. RUL estimation and uncertainty obtained with the gamma process when parameter  $b$  is calculated with the weighted least-square optimization (red lines) and when it is fixed to 2.2 (black line). The actual RUL is indicated by the green dashed line.