MAINTENANCE ANALYTICS TO PREDICT FAILURE OF A PINCH VALVE SLEEVE

HUOLTOANALYTIIKKAMENETELMÄT LETKUVENTTIILIN LETKURIKON ENNUSTAMISEKSI

Lappeenranta-Lahti University of Technology LUT
LUT School of Energy Systems
Bachelor’s Programme in Mechanical Engineering, Bachelor’s thesis
2023
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Examiner: D. Sc. (Tech.) Harri Eskelinen

ABSTRACT

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Mechanical Engineering

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Bachelor's thesis

2023

39 pages, 14 figures and 1 appendix

Examiner: D. Sc. (Tech.) Harri Eskelinen

Keywords: Pinch valve; Maintenance analytics; Segmented regression; Diagnostic data

In this thesis, first steps are taken into the research about the viability of the Neles™ ND9000-positioner's diagnostic data in predicting failures to the Flowrox™ heavy-duty pinch valve sleeve. The thesis provides insight into Valmet's Flow Control business line and the aforementioned valve and positioner. Theoretical background into the failure mechanisms is provided, and the analytic methods suitable for data from the positioner are selected through exploring the matter in a literature review. Finally, an analysis program is presented, based on the methods for analysis described.

Should the sleeve fail according to the failure mechanisms hypothesized, the analysis program should be able to present models fitted to the data using segmented regression. The difference of models can then be used to visually determine whether the sleeve is about to break. Using the tools developed, as sufficient data is gathered in the future, this feature could be implemented into the positioner to warn about the sleeve nearing the end of its life. This could help industrial plants minimize costs due to unscheduled stops in the process caused by a sleeve breaking.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Pyry Mustonen

Huoltoanalytiikkamenetelmät letkuventtiilin letkurikon ennustamiseksi

Kandidaatintyö

2023

39 sivua, 14 kuvaa ja 1 liite

Examiners: Tarkastaja: TkT Harri Eskelinen

Avainsanat: Letkuventtiili; Huoltoanalytiikka; Osittainen regressio; Diagnostiikkadata

Tässä kandidaatintyössä otetaan ensimmäiset askeleet tutkimukseen, jossa pyritään määrittämään Neles™ ND9000 -asennoittimen diagnostiikkadatan hyödyntämisen toimivuus, Flowrox™ heavy-duty -letkuventtiilin letkurikon ennustamisessa. Työssä esitellään Valmetin virtauksensäätöliiketoimintalinja sekä edellämainittu letkuventtiili ja asennoitin. Letkun rikkoutumismekanismeja avataan teoreettisella pohjalla, jonka jälkeen asennoittimen datan analysointiin soveltuvat menetelmät määritetään kirjallisuuskatsauksen pohjalta. Lopuksi esitetään näihin mentelmiin perustuva analyysiohjelma.

Mikäli letku rikkoutuu oletetulla tavalla, esitetty analyysiohjelma pystyy osittaisella regressiolla dataan asetettujen mallien perusteella ennustamaan letkun rikkoutumisen. Käyttäen esitettyjä työkaluja, mikäli riittävä määrä dataa saadaan kerättyä tulevaisuudessa, tämä ennustusmenetelmä voidaan sisällyttää itse asennoittimen ohjelmistoon. Tämä ominaisuus voisi varoittaa teollisuuslaitoksen ylläpitoa letkurikosta johtuvista yllättävistä pysähdykistä, minimoiden niistä aiheutuneita ylimääräisiä kustannuksia.

ACKNOWLEDGMENTS

I would like to express my gratitude towards Jarmo Partanen, Johanna Puranen, Marko Rissanen and Anssi Tujula at Valmet Flow Control Oy, for providing me with the opportunity, resources and tools to work on this topic.

I would also want to thank the supervisor of this thesis, Harri Eskelinen, for his support and guidance.

Last but not least, I want to thank my family and friends for both their direct and indirect support.

SYMBOLS AND ABBREVIATIONS

Roman characters

A	area	[mm²]
c	compression	[mm]
d	deviation	[%]
D	diameter	[mm]
f	force	[N]
p	pressure	[bar, Pa]
P	position	[mm]
t	length of a period	[data steps]

Dimensionless quantities

n	point in the data

Subscripts

1	at cylinder front end
2	at cylinder back end
a	actual (measured)
net	net (force)
p	percentage
r	piston rod
t	target

Abbreviations

DTM Device Type Manager software

HART Highway Addressable Remote Transducer protocol

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1 INTRODUCTION

The mining and metal industries set unique challenges for flow control technology. When transporting slurries that carry solid materials, control valves designed for gases and clean liquids, such as globe valves, can get stuck easily. In some cases, turbulence in the flow through the valve can also be the cause for increased erosion, requiring expensive and exotic construction materials to be used (Flowrox™ Experts 2023). Valmet Flow Control's Flowrox™ pinch valves, however, have offered a solution to these problems for over forty years.

In modern industrial processes, the valves are often connected to a process automation system. The valve can be fitted with a positioner (also referred to as a valve controller), a device used to set the position of the valve to a value given by the automation system. The positioner can also send information, such as the valve position, back to the automation system.

Valmet Flow Control's product portfolio also includes Neles™ control valve positioners, which offer many diagnostic parameters that can be read from the device in real time. The purpose of this diagnostic information is to help the operators notice faults or damage in the valve and make it easier to pinpoint the cause of them. Accomplishing this helps minimize unscheduled stops in the process, which can be very costly for the company running the plant (Loudin, T. 2023). In the case of Flowrox pinch valves, these diagnostic parameters offered by the ND9000-series positioners have not yet been explored for use in a real-time fault detection and prediction feature, which could save valuable time currently taken by unscheduled repair of broken equipment. To assess the viability of such feature in the case of the Flowrox heavy-duty pinch valve, it must be determined whether the beginning phases of these faults can be detected by the valve's positioner. This is done by analyzing the vast amount of diagnostic data that the positioner can output, as ”Data mining (- -) can discover knowledge in terms of new patterns and relations not visible at a glance”, according to Karim et al. (2016).

1.1 Research objectives

The aim for this thesis is to develop methods to determine whether the event of the valve's sleeve breaking can be seen in the diagnostic data provided by the ND9000-series positioner. The aim is expected to be achieved by answering to the main research question:

How can the event of a pinch valve sleeve breaking be detected from the positioner's diagnostic data?

To aid in the finding of the answer to the main question, two sub-questions to are also presented:

1) How can an abnormal change in the closing force be found in the diagnostic data?

2) How can an abnormal change in the position target deviation be found in the diagnostic data?

To determine the answers to this question, predictive maintenance analytics methods are explored in the form on a literature review. During the review, a method suitable for the type of data that the positioner outputs is selected. Based off of the results of the review, the selected methods are then applied to developing the analysis methods in the context of the positioner's data. These analyses aim to determine a correlation between the parameters' changes and the sleeve breaking. To visualize the results, a MATLAB analysis program is created.

1.2 Research limitations

Despite the pinch valve being a widely used product in many industries, very little public research has been carried out regarding their properties. Also, as this research is solely conducted on Flowrox™ valves, there may be uncertainty of said information's validity concerning application to Flowrox valves. This means that the theoretical basis of this thesis is largely dependent on the information gathered from experts on the properties of the Flowrox valve. Due to some information being proprietary, the amount of credible technical experts is limited to individuals found within Valmet Flow Control who are qualified with expertise on the Flowrox pinch valve.

As mentioned in the objectives, the methods created in this research are theoretical and based on the behaviour of the sleeve hypothesized by experts and applications of information found in literature. While being out of the scope of this research, the analysis methods must be tested with data collected from physical testing of valves to definitively state their functionality. Additionally, tweaking of parameters within the analysis programs may be necessary depending on the model of valve studied or to improve their function after testing with real data has been conducted.

If the prediction of sleeve failure using the positioners data is established to be possible, the methods developed in this research could then be implemented into the positioner. However, this would likely require the code to be written in a different programming language. For this reason, the consideration of the functionality of the code in the positioner's own software, or the implementation of the code into the positioner is not in the scope of this thesis.

1.3 Valmet's Flow Control business line

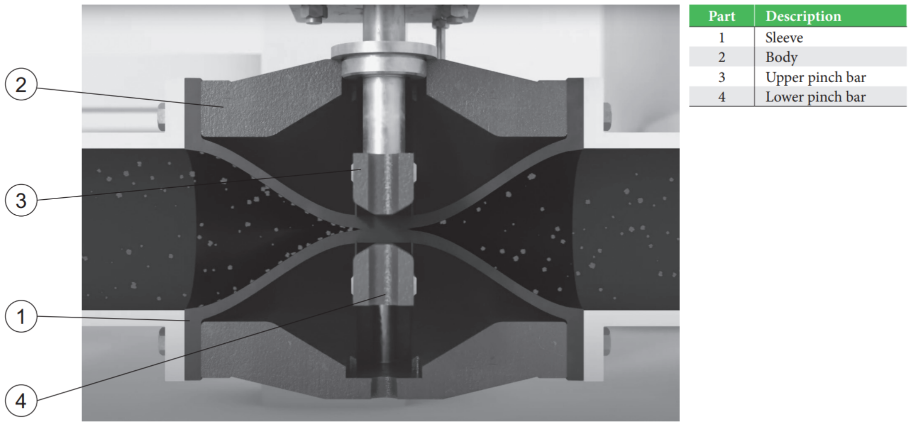
The Valmet Flow Control business line was formed when Neles was merged into Valmet in April of 2022. The process industries in which Valmet Flow control operates include pulp, paper and bio-products, renewable energy, oil and gas refining, chemicals and mining and metal processing. The products aimed at the mining and metals segment includes Flowrox™ valve and pump solutions. Formerly known under the company name Larox Flowsys, Flowrox, as an independent company and now a brand, has a history of over 40 years in flow control with elastomer technology. The Flowrox brand has been owned by Neles Group since 2021, and as of April 2022, operates as a part of the Valmet Flow Control business line. (Valmet Corporation 2023a)

1.4 Flowrox heavy-duty pinch valve

Figure 1: Flowrox™ heavy-duty pinch valves with Neles™ ND9000 positioner (Valmet Corporation 2023b)

The most popular of products within the Flowrox catalog is the heavy-duty pinch valve, shown in figure 1. At the heart of a pinch valve is an elastomer sleeve, that is installed in the pipeline of the process. When pinching the sleeve shut (Figure 2), the compliant material of the sleeve forms around the possible solid particles, allowing it to stop the flow despite the solids present.

When fully opened, the valve also allows for fully undisturbed flow in the pipeline. This means that there is no added turbulence, greatly reducing erosion caused by the possible solids carried by the medium. Additionally, thanks to their straight-through design, pinch valves have no cavities for solid particles to settle and build up into. The unique working principle of a pinch valve allows it to function with amounts of solid content that would usually result in a clog or a leak, when using other types of valves. (Flowrox™ Experts 2023)



Part	Description
1	Sleeve
2	Body
3	Upper pinch bar
4	Lower pinch bar

Figure 2: Flowrox heavy-duty pinch valve with its sleeve fully shut (Valmet Flow Control Oy 2023)

Another benefit of a pinch valve is that its only regularly wearing item is the sleeve. For this reason, the ability to predict the breaking of the sleeve would reduce unexpected faults to nearly zero, when operating within the designed life of the valve's components.

1.5 Neles ND9000-series intelligent valve controller

Figure 3: Neles™ ND9000-series intelligent valve controller (Valmet Corporation 2023c)

With the merging of Neles into Valmet, the Flow Control business line also acquired the Neles™ positioners into its product portfolio. Although being recently succeeded by the Neles NDX-series, the ND9000-series positioner, as shown in figure 3, is still a volume product that is widely used globally across many industries. Being a modern intelligent controller device, it has the ability to interpret and track the parameters within itself to provide diagnostic information to the user (Valmet Corporation 2023c). This is accomplished by illustrating these parameters as values depicting the health of the valve. These parameters can also be read and saved into a log in their raw form. These parameters include information such as the target and actual position of the valve, operating pressure and temperature. The ND9000-series positioners have the ability to log four parameters simultaneously. The Neles ND9100 valve controller, a model of the ND9000 series, is the current standard option for Flowrox pinch valves. Naturally, to reap the greatest benefit from the results of this thesis, it is the model chosen for examination.

2 THEORETICAL BACKGROUND

This chapter describes the theoretical background behind the choice of the two phenomenons for the sub-questions. The aim for this chapter is to tie the phenomenons assumed to be found in the data, with physical events caused by changes in the sleeve's structure.

2.1 Sub-question one: closing force

As the valve's operation relies on the deformation of the sleeve, one of the key properties changing with the condition of the sleeve is its stiffness. During operation, the sleeve's inner lining, shown in figure 4, wears off with the medium travelling through it, and the pinch bars causing frictional wear on the outer surface. As this wear is happening, the sleeve becomes easier to pinch shut, which can be seen as a reduction in the required closing force. (Flowrox™ Experts 2023)

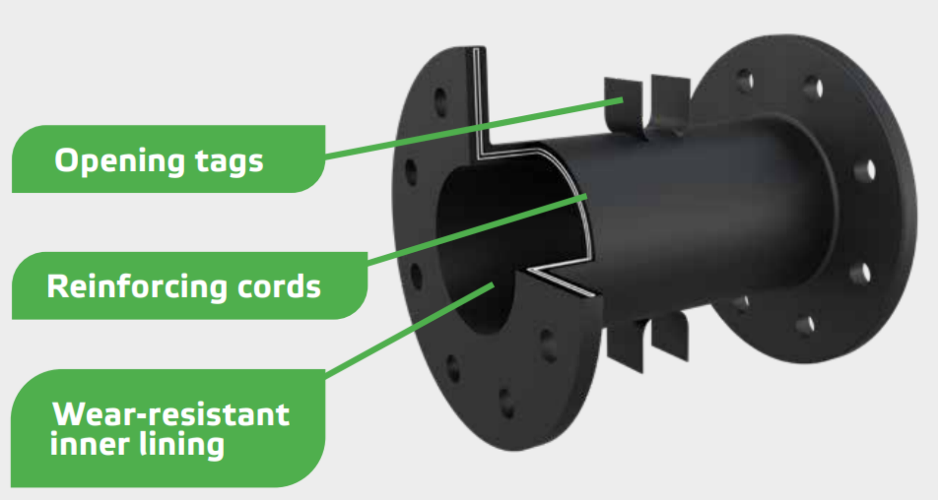


Figure 4: Construction of the Flowrox™ pinch valve sleeve (Valmet Flow Control Oy 2023)

When the valve and sleeve are set up according to the installation manual, the most common cause of failure of the sleeve is the wear of the inner lining rapidly tearing apart. This happens due to the lining wearing thinner at the pinch bars, which causes the sleeve to not shut tightly. This leak in the sleeve causes high velocity medium to punch a hole to the inner lining, on the exit side of the sleeve. From this initial hole, the inner lining will rapidly start tearing and the stiffness of the sleeve will be greatly reduced in a short amount of time. For sleeves of standard construction and largely depending on the conditions such as the solid content and pressure of the medium, this happens at an estimated 50 to 5000 cycles. (Flowrox™ Experts 2023) As the cycle rate used in this experiment is the aforementioned 164 cycles per hour, the time taken by the event of the sleeve breaking can range from 18 minutes, up to 30 hours. As the medium used in the stress test is of zero solid content and low pressure, this time can be assumed to be near the longer side of the estimated range.

As the opening action is identical to the closing action only reversed, the opening force is affected by the same changes in the sleeve's condition as the closing force. In addition, any force acting to open the valve is assisted by the pipeline pressure naturally pushing on the sleeve to open it. This results in the actuator having to slow down the movement by applying closing force, making the opening force irrelevant for examination. For these reasons, only the required closing force is analyzed for abnormal changes.

2.2 Sub-question two: position target deviation

The position target deviation is an important value for all valves. The deviation is defined by calculating the absolute value of the difference between the target position and the actual position of the valve, as shown in equation 2.1.

$$d_p = |P_t - P_a| \tag{2.1}$$

where d_p position target deviation [%], P_t is the target position [%] and P_a is the actual position [%].

The target value is the desired value the valve is trying to reach, given by the process automation system for example. The actual position of the valve may deviate from that for a number of reasons, for example if the actuator is malfunctioning. Ideally, if the valve is able to follow the target with absolute accuracy, the deviation value will be 0. Thus, the less the absolute value of deviation is, the better. While there can be useful information found in whether the value is negative or positive, in this case all deviation is considered to be not desirable. Thus, the value for the position target deviation is calculated as its absolute value.

The sleeve of a pinch valve may also be prematurely worn due to cavitation. Cavitation is a phenomenon, where the sleeve is violently shaken by rapid changes in the pressure within it. This only happens when the valve is set to near its fully shut position, with flow through the valve still present. According to Bernoulli's principle, the flow is accelerated during its entry to the valve, as the sleeve's cross-sectional flow area is reduced along the plane of the pinch bars' movement. As the rapid flow exits the smallest area and moves towards the exit side of the sleeve, where the flow area is the full bore of the pipeline, it is again decelerated (Clancy 1975). Due to the inertia of the flow medium, the deceleration is not instant and thus leads to areas of partial vacuum within the exit side of the sleeve. These partial vacuums may reduce the pressure so radically that the medium reaches its boiling point. As these gas bubbles reach an area of more pressure, they violently implode, causing dramatic pressure fluctuations of up to 1000 bar, in the flow. When these implosions happen near the sleeve's inner lining, they can cause damage to the sleeve. (Flowrox™ Experts 2023)

As the positioner is trying to hold the valve position in a set point during cavitation, these pressure changes will be visible as rapid changes in the required closing force.

3 PREDICTIVE ANALYTICS METHODS OF DIAGNOSTIC DATA

The article by Karim et al. (2016) discusses the use of analytics as a tool to help with decision-making considering maintenance applications. Karim et al. (2016) presents four perspectives, by which maintenance analytics can ”addresses the process of discovery, understanding, and communication of maintenance data”. The four perspectives presented by Karim et al. (2016) are:

1. Maintenance Descriptive Analytics, to discover and describe what happened in the past.
2. Maintenance Diagnostic Analytics, to understand why something happened.
3. Maintenance Predictive Analytics, to estimate what will happen in the future.
4. Maintenance Prescriptive analytics, addresses what need to be done next.

As the analytics problem at hand focuses to determine what will happen to it in the future, the problem can be tackled with predictive analytics methods. As for the process in which these methods can be applied in, Karim et al. (2016) writes: ”The process of knowledge discovery will essentially consists of; data acquisition, to obtain relevant data and manage its content; data transition, to communicate the collected data; data fusion, to compile data and information from different sources; data mining, to analyse data to extract information and knowledge; and information extraction and visualization, to support maintenance decision.”

Applying this process in the context of this research, the steps could be performed in practice by the following description. Data acquisition can be performed by placing the valve into a stress test, data transition by using a Highway Addressable Remote Transducer protocol (HART) modem to translate the information to a form that a computer can understand. In this case, as the positioner is the only source for data, the step for data fusion can be skipped. The data mining and information extraction and visualization will be performed with an analysis program that visualizes the changes in the data for decision-making.

For the last steps of data mining and information extraction, a viable numerical analysis method for the data must be chosen, in order to conduct an empirical study with the data. To explore different options and select a viable method, a form of systematic literature review is performed, as it can act as a background for an empirical study (Templier 2015), which is the case for the future research of the topic of this thesis.

3.1 Review process

This section covers the process of the review conducted. As the aim for this review is to explore existing, successfully implemented methods in a new context of pinch valves, the review will follow guidance for narrative reviews as given by Templier (2015). As no research on the predictive maintenance analytics of the Flowrox pinch valve has been done previously, the scope of this review must broadened to all types maintenance analytics.

According to Levac et al. (2010, p. 3), the review should state answers to the questions such as: ”where to search, which terms to use, which sources are to be searched, time span, and language”. These questions will be answered in the subsections to follow.

3.1.1 Search terms and filters

The search terms for this review are derived from the main topic of this thesis. As the aim for the thesis is to create methods for predictive analysis of diagnostic, maintenance related data, the publications reviewed must contain information about data analysis and handling. Due to the data rarely being referred to as ”diagnostic”, the term ”maintenance” is used instead. By combining the conditions above, the publications must be found with the following terms:

*”STATISTICAL” ”DATA HANDLING” ”MAINTENANCE” ”PREDICT***”*

For the most efficient search of literature, the search terms are combined using Boolean operators (”+” or ”AND”). This way, the search find relevant papers without excluding papers based on differences in sentence structure, as could possibly be the case with a sentence such as: ”Handling and prediction of statistical maintenance data”. The term ”predictive” is cut with wildcards (”*”), in order to also include word ”prediction”. The terms are searched from the title, abstract and keywords of the publications.

There must be filters set for the literature found from these databases in order to select the ones relevant for this research, and to exclude irrelevant ones. The publication in examined must be written in the subject area of engineering or computer science. The time span is left undefined, as the matter is not dependent on any single technology, from a set era. The sources must be peer-reviewed articles, academic books or technology conference papers. Language of the publications included must be English.

3.1.2 Databases

The database used for this literature review is Scopus as it is the database with the greatest amount of publications on the matter that offer access to full texts provided by LUT Academic Library. Web Of Science database was also explored, however the amount of publications it returned was not satisfactory.

3.1.3 Criteria for inclusion or exclusion

To be included in this review, the publications must contain use of data-analysis in predictive maintenance and monitoring. Articles using machine learning, statistical prediction or probabilistic logic are excluded, as they are based on large training sets. As the pinch valve sleeve's wear rates and behaviour are largely dependent on conditions, gathering and implementing large training sets is not a viable approach. To be included, the methods must use predictions drawn from the data set at hand as the primary source of data for the decision-making body of the analysis program presented in the article.

3.1.4 Assessment of relevance

The search results with the aforementioned filters yielded 59 publications. Out of those, 45 were deemed irrelevant based on the title. The publications excluded by their titles contained terms referring to models used in machine vision algorithms used for maintenance purposes or bio-science. These are not relevant information, as the data analyzed is not directly derived from the physical properties of the item examined for wear.

Nine articles were excluded based on the abstract. The articles covered analysis of data, but the methods for example, forms of multivariable analysis or machine learning, were not applicable for use in this context.

The five remaining articles were assessed based on the full text, and out of those, two were excluded. These texts applied linear models and diagnostic data, but combined them with Bayesian interference or machine learning, deeming them irrelevant.

This results in three publications being found as relevant, considering the topic of this thesis. The screening and assessing process are visualized in figure 5 as advised by Liberati et al. (2009).

The low number of publications included is likely due to the narrow research topic and inclusion criteria. While analysis of data for predictive maintenance purposes is common, it is rarely applied in a way that is not a part of machine learning or probabilistic approaches. However, the three publications included provide valuable indications to methods to use in predictive diagnostic data analysis with pinch valves.

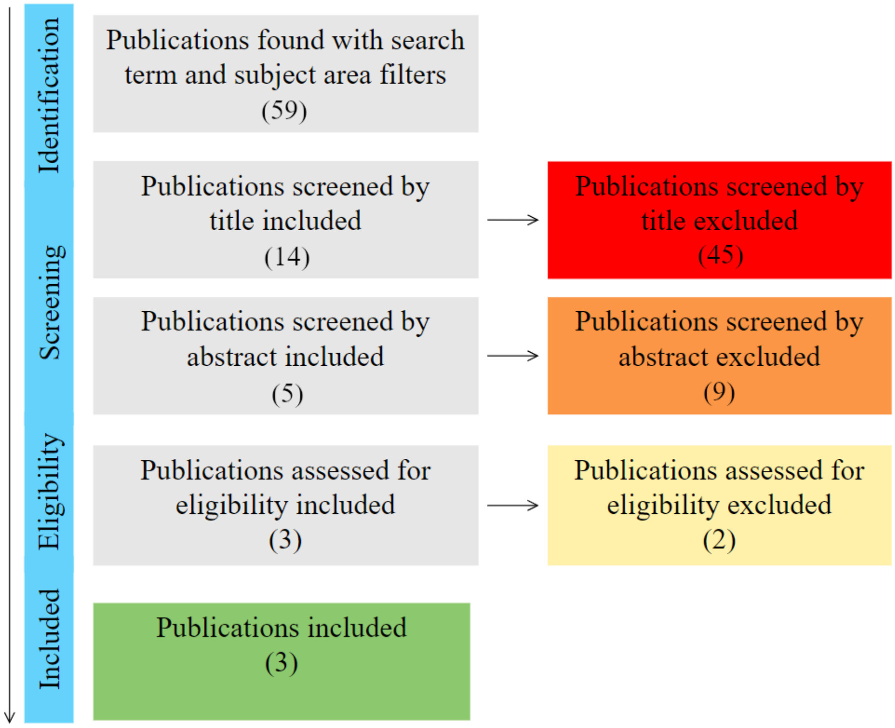


Figure 5: Flowchart of steps 3 (screening for inclusion) and 4 (assessing for quality), as described by (Templier 2015).

3.2 Results and extraction of data

The publications found relevant, and their information can be seen in figure 6.

The papers all present forms of segmented regression used to predict failures of components. It must be noted that all of the articles are written in affiliation to the National Aviation University of Kyiv, Ukraine. While having records from scattered sources is usually considered more credible, in this case, all of the publications sharing some information may be beneficial. The articles all successfully implement the same basic principle of segmented regression analysis on different applications with Solomentsev et al. (2022) focusing on telecommunication systems, Zaliskyi et al. (2022) on aviation equipment and Kuzmin et al. (2019) on wind turbines. The fact that the method of segmented regression can successfully be applied to analytics of diagnostic data across fields, should indicate its potential in the application of pinch valves.

ARTICLE TITLE	AUTHOR	YEAR	PUBLISHED IN	PUBLISHER
Model Building for Diagnostic Variables during Aviation Equipment Maintenance	Zaliskyi, M., Solomentsev, O., Larin, V., Averyanova, Y., Kuzmenko, N., Ostroumov, I., Sushchenko, O. and Bezkorovainyi, Y.	2022	2022 IEEE 17th International Conference on Computer Sciences and Information Technologies (CSIT)	IEEE
Statistical Analysis of Wind Turbine Operational Data	Kuzmin, V., Zaliskyi, M., Kozhokhina, O., Shcherbyna, O., Odarchenko, R.	2019	2019 IEEE 15th International Conference on the Experience of Designing and Application of CAD Systems (CADSM)	IEEE
Predictive Maintenance Approach for Telecommunication and Radioelectronic Systems	Solomentsev, O., Zaliskyi, M., Zuiev, O., Shcherbyna, O., Odarchenko, R., Yashanov, I.	2022	2022 IEEE 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET)	IEEE

Figure 6: The title, authors, year, book and publisher of publications included.

While all three previously mentioned publications use the same basic principle, Solomentsev et al. (2022) also applies the method to a similar data set as those assumed to be given by the positioner during a stress test. The behaviour is described by Solomentsev et al. (2022, p. 59) as follows: ”there is transition from normal operation stage to wear-out when the failure rate stops being constant and starts to increase.”, which is visualized in figure 7.

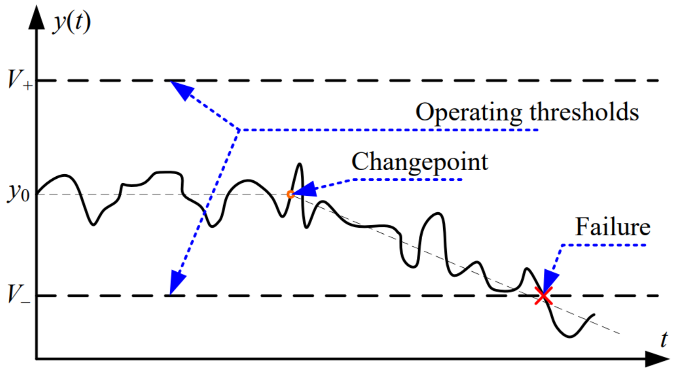


Figure 7: Example of diagnostic variable trend (Solomentsev et al. 2022)

The behaviour of the sleeve during the stress test is assumed to be identical to the behaviour of data described by Solomentsev et al. (2022). As the sleeve also wears linearly with an operation stage and a changepoint, after which the wear rate increases, the method is assumed to be viable for the research problem at hand.

4 ANALYSIS OF THE GATHERED CLOSING FORCE DATA

As the closing action is preformed by the actuator, in this case a pneumatic cylinder, the closing force is directly related to and caused by the pressure applied to the cylinder. To determine the closing force, the cylinder's front and back ends must be assigned as shown in figure 8.

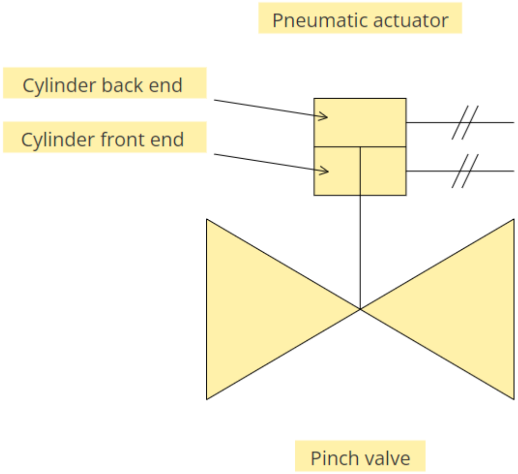


Figure 8: Pneumatic actuator chambers' label assignment

In this case, the cylinder is a standard single-piston, double-acting cylinder. The front end is considered to be the chamber on the side nearest to the valve, with the piston rod going through the chamber's end cap. The back end is the chamber on the other side, further from the valve. With this arrangement, any pressure applied to the back end chamber of the cylinder will force the piston rod out of the cylinder, which results in a closing action. Any pressure applied to the front end chamber will force the piston rod back in, counteracting the closing action.

The net closing force, which is the balance between the pressures within the chambers, can be calculated by subtracting the actuator's front end pressure and area from the back side pressure and area, as shown in equation 4.1 (Majumdar, S.R. 1996).

$$F_{net} = p_2 A - p_1 (A - A_r) \tag{4.1}$$

where F_{net} is resulting closing force [N], p_2 pressure within the back end chamber of the actuator [MPa], p_1 pressure within the back end chamber of the actuator [MPa], A the actuator's effective piston area [mm²] and A_r the actuator's piston rod area [mm²].

As the closing force is considered to be a net force closing the valve, to avoid confusion, any negative values in the closing force are referred to as opening force.

4.1 Filtering of the closing force data

As the pressures applied to the chamber's of the cylinder are determined by the positioner and these parameters being logged, the closing force can now be determined in any point of the test using the collected pressure data as shown in equation 4.1. However, much of this data is not of interest, as the greatest amount of force is required to compress the sleeve tightly to close against the pipeline pressure. This is achieved by compressing the sleeve slightly further than its first closing point. For a 50 mm diameter sleeve, this compression is set at 3.5 mm (Valmet Flow Control Oy 2022).

$$c_{(\%)} = \frac{c}{D_s + c} = \frac{3.5\text{mm}}{50\text{mm} + 3.5\text{mm}} = 0.06... \approx 6\% \tag{4.2}$$

where $c_{(\%)}$ is the amount of travel, where the compression of the sleeve is present, relative to the full actuator travel [%], D_s is the diameter of the sleeve [mm] and c is the absolute amount of travel, where the compression of the sleeve is present [mm].

As shown in equation 4.2, this means that the extra compression happens approximately at the last 6% of closing travel, which means that values for points where the valve position is under 94% of the travel, can be ignored.

Furthermore, as the valve position value above 94% may be reached both on the closing and opening stroke, the values read on the opening stroke must be filtered out. This can be achieved by stating that the next value for target position, must be higher or equal to the one examined.

Whether a value in the data meets all of the previously mentioned conditions, can be tested with the logical statement:

IF $P_a(n) > 94\%$ **AND** $[P_t(n+1) > P_t(n)$ **OR** $P_t(n+1) = P_t(n)]$

where $P_a(n)$ is the actual position at the point of time n [%],$P_t(n)$ is the target position at the point of time n [%], and $P_t(n)$ is the next available value of target position [%].

If at the point in time n, this statement returns true, the value of closing force for that point in time will be appended to an array of closing forces of interest. If the statement returns false, these values will be discarded. After either of those actions, these steps, beginning from the logic test, are then repeated for the point of time $n + 1$. This procedure is repeated until n is equal to the amount of rows of data, meaning the end of available data has been reached.

4.2 Numerical analysis of the closing force data

Because the required closing force is hypothesized to decrease linearly as the sleeve's inner surface wears down and becomes thinner, any abnormal change is defined by the closing force deviating from this linear change. This behaviour, being identical to that described by Solomentsev et al. (2022), means that the analysis can be carried out following the example set in the article.

To analyze the data for these abnormal changes in a way that, in the future, could be possibly replicated by the positioner in real-time, the data is divided into two parts as is the practice in the article by Solomentsev et al. (2022). The data is divided into a reference period and a wear-out period. The reference period is the full history of closing force values, from which a function for linear wear can be determined. The wear-out period is an array of closing force values from the end of the test, from which the current rate of wear can be determined. The current wear rate from the end of the test, where the sleeve has failed, can then be compared to the reference wear.

The length of these periods are set as a baseline with consideration to the cycle rate mentioned in chapter 2. They should therefore be tweaked in the future, should possible further research with more field-realistic cycle rates provide a need to do so. In this research, the length of the wear-out phase is referred to as t_x.

As the log from the positioner is updated every second, for a set from 1 to n of values logged, the reference values are set to be from 1 to $n - t_x$ and the wear-out values as $n - t_x$ to n. A linear model is then fitted to both of these data sets, and their slopes cross-examined.

For the situation described, the graph should appear similar to what can be seen in figure 9, note the similarity of concept with figure 7, by Solomentsev et al. (2022).

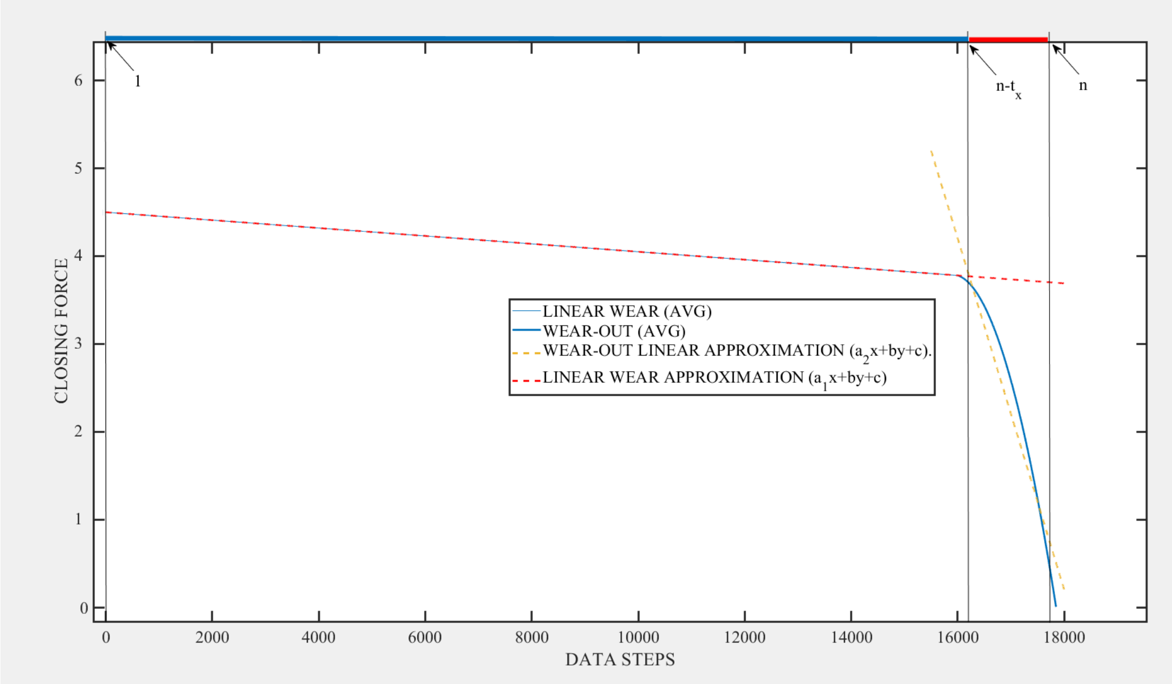


Figure 9: The linear models for the reference wear 1 to n-t_x in blue and the wear-out phase n-t_x to n in red

The linear wear rate can be seen as a_1 of the linear model's definition, seen in the red area between 1 and $n - t_x$. The wear rate for the event of the sleeve breaking can be seen as a_2, defined by the linear model seen in the yellow area. With the difference being that the closing force does not have an upper threshold, the graph should otherwise appear identical to the one shown in figure 7.

To determine the most accurate method for analysis, the value for t_x is chosen based on the data from the cyclic stress test. If the period is set too long, there will be a considerable length of the reference wear present in the data, reducing the difference between the slopes a_1 and a_2. If, however, set too short, the system is more sensitive to changes in a smaller time scale, possibly leading to false positives. Thus the most desirable length for the current period is that, in which there is as much of the data from the event of the sleeve breaking, along with as little as possible of the reference data.

5 ANALYSIS OF THE GATHERED POSITION TARGET DEVIATION DATA

For position target deviation, much of the same methods of analysis can be used as for the closing force. However, as the deviation at all points is of interest, different filtering of the data must be carried out. Additionally, the position target deviation data is also examined for the possibility of cavitation.

5.1 Filtering of the position target deviation data

The position target deviation should decrease linearly along with the closing force, due to the sleeve wearing thinner. This makes the sleeve less stiff and it is thus easier for the actuator to move. Being easier to move helps reduce the system response time, which then reduces position target deviation. This means that any abnormal change could be again described as a radical change in the rate of change within a short time period. To examine the data for these changes, the same principles will be applied as for the closing force data. However, in the case of position target deviation, the data will not be filtered for position. Instead, all of the data will be examined.

Another interesting phenomenon, possibly noticeable in the data of position target deviation, is cavitation. To examine the data for the for changes in cavitation, the data must be filtered into two parts. As mentioned before, the cavitation only occurs when the valve is close to its fully shut state. The window where the cavitation is able to happen is from 96% to 98% of travel. This window has been determined by testing on the the test valve and thus will vary between valves in the model range.

This means that cavitation can be seen when the values for position deviation in the window mentioned are considerably higher than those outside of the window. To eliminate as many other variables as possible, the reference window will be set from 84% to 94%. This way the set examined for cavitation and the reference set are as similar as possible, with potential differences in the behaviour filtered out compared to the values at other parts of the valve travel range.

To filter the data for the described situation, it can be tested with two logical statements:

IF $P_a(n) > 94\%$ **AND** $P_a(n) < 98\%$

where $P_a(n)$ is the actual position at the point of time n [%], and $P_a(n)$ is the next available value of position [%].

If at the point in time n, this statement returns true, the value of target position deviation for that point in time will be appended to an array of deviations with possible cavitation. If the statement returns false, the value at n will be tested for the logical statement:

IF $P_a(n) > 84\%$ **AND** $P_a(n) < 94\%$

where $P_a(n)$ is the actual position at the point of time n [%], and $P_a(n)$ is the next available value of position [%].

If this statement returns true, the value at the point n will be appended to an array of reference values. If the statement returns false, the value will now be discarded. After either of those actions, these steps, beginning from the logic test, are then repeated for the point of time $n + 1$. This procedure is repeated until n is equal to the amount of rows of data, meaning the end of available data has been reached.

5.2 Numerical analysis of the position target deviation

With the filtering of the data completed, the steps of the numerical analysis will follow those performed in the analysis of closing force. As there are two analyses to be carried out on the position deviation, one for the deviation itself and one regarding cavitation, there will be three analyses in total.

6 THE CYCLIC STRESS TEST

This section describes the cyclic stress test performed on the valve, from where the required data can be gathered. The section is divided into two subsections, each covering the hardware and software of the test respectively. With the data gathered from this test in the future, the functionality of the analysis methods developed can be confirmed.

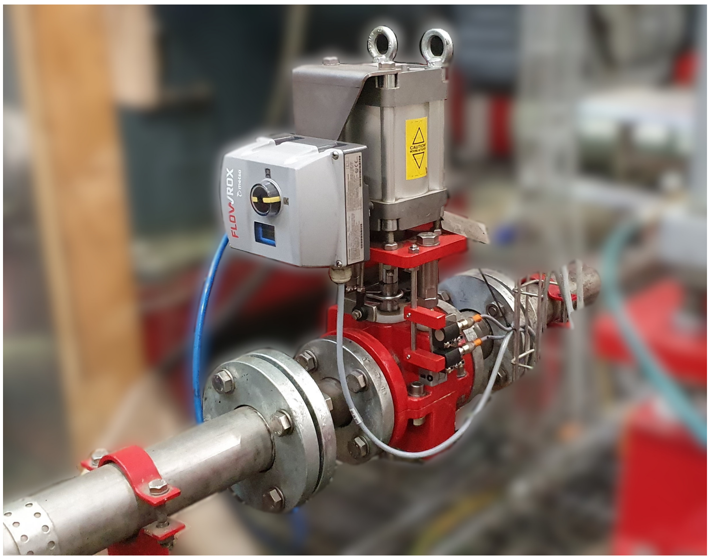


Figure 10: Flowrox heavy-duty pinch valve with Neles ND9000 valve controller in the cyclic stress test.

6.1 Hardware

The stress test is modeled to simulate a real-world industrial pipeline. The test requires piping, a substance that is pumped through the system, a pump to drive the said substance and the valve to be tested. The pumped substance used in this case is water. The two acting components in the process are the pump and valve, with the piping laid out to form a loop around the two aforementioned components, as shown in the flow diagram (figure 11).

Visible in figure 10, the valve used in this test is a Flowrox heavy-duty pinch valve, with an enclosed body and a sleeve diameter of 50 mm. Closing and opening action is powered by a pneumatic cylinder with a 100 mm piston diameter, which is mounted to the top of the valve. The valve is fitted with a Neles ND9100 positioner, which receives the 4-20 mA operating signal from an external logic device. A computer is required for reading and saving the diagnostic parameters in real time. The positioner outputs this information through a

HART-signal, embedded into the current signal it receives. To decipher the HART-signal from the current signal, a HART-modem to be used to translate the signal to a digital data stream, understood by the computer. The HART connection for the logging device is wired in parallel with the current signal that is sent to the positioner from the logic board, as shown in figure 11.

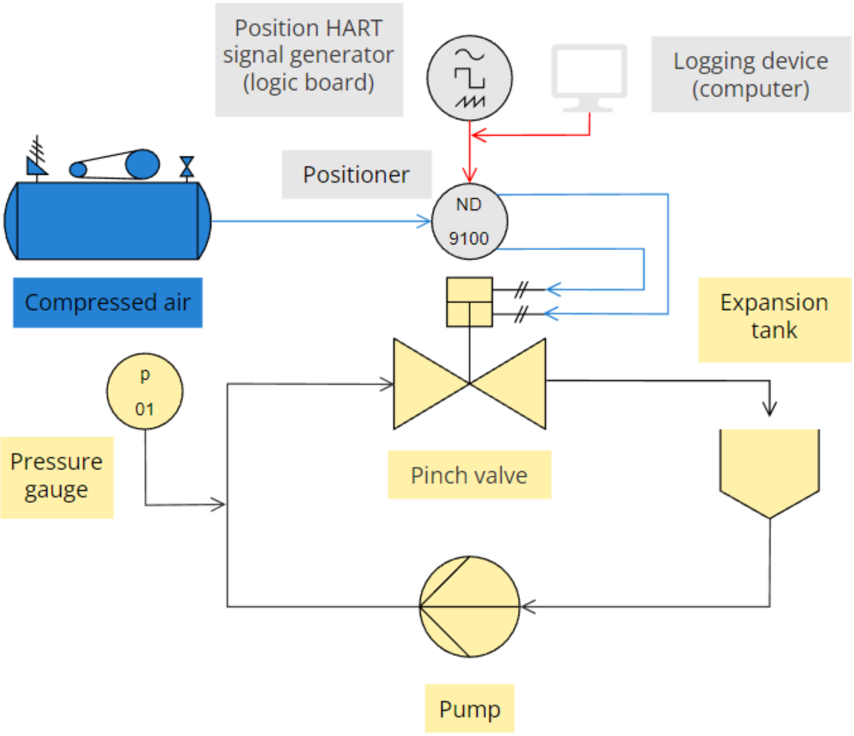


Figure 11: The stress test process flow diagram and components

Though optional, to ensure safety and to minimize damage to the test equipment, a capacitive sensor is attached to the bottom of the valve. This sensor cuts the power to the pump in case the sleeve is broken and the water leaks out of the system into the valve body, preventing the pump from being damaged due to dry running.

6.2 Software

The current signal from the logic device, as shown in 12, is a ramp signal with a rate of change of 4 mA/s to open and close.

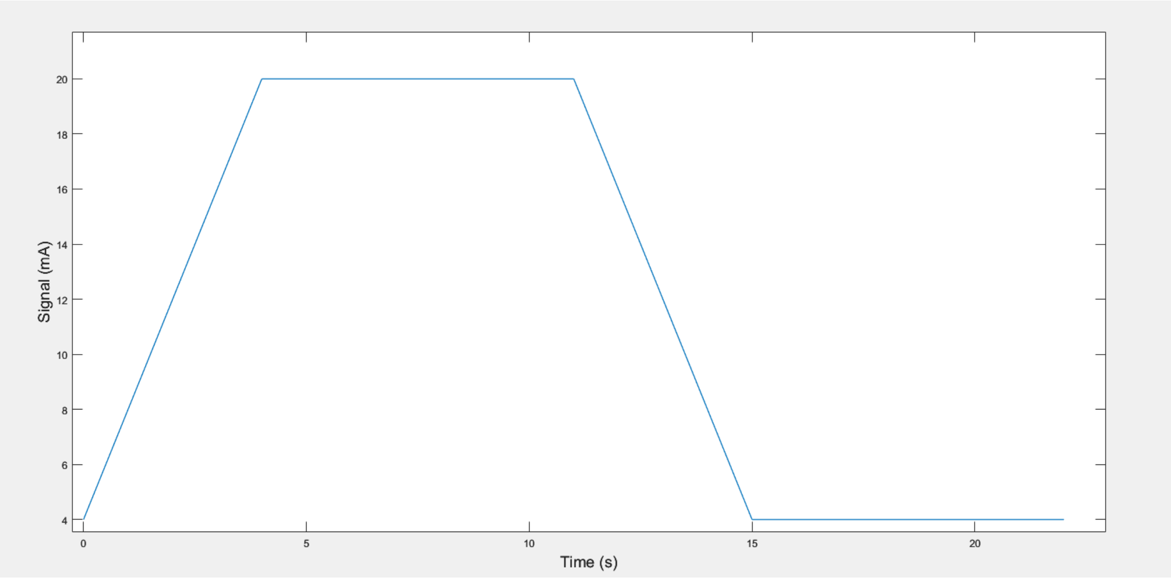


Figure 12: The 4-20 mA current signal from the logic device to the positioner input

This drives the valve open and closed smoothly, providing more accurate information about the force required to close the valve. There is a seven second still period in both open and closed states. With this rate, the operation of closing and opening the valve takes 22 seconds in total, resulting in approximately 164 cycles performed hourly.

The positioner's data can be read using the Device Type Manager software (DTM) provided by Valmet Flow Control for the ND9100. The four parameters chosen for logging are: target position for the valve, actual position of the valve and pressures from both chambers of the pneumatic actuator.

7 DISCUSSION

In this chapter, discussion is initiated about the results of the literature review and the methods described in the previous chapters. The limitations of the methods, possible improvements to the resulted practices in analytics and points for further research are also considered. The answers to the research questions are also presented, along with a practical application of the methods. This practical application proposal is in the form of an analysis program which is able to examine the data for changes in trends and providing the ability to visually predict the breaking of the sleeve.

7.1 Literature review

As established in chapter 3, there is a limited amount of previous research concerning analysis methods applicable to data sets, such as ones offered by the positioner diagnostics. As evident by the amount of articles excluded, predicting failures and maintenance requirements by machine learning and probabilistic approaches seems to currently be the preferred method. However, segmented linear regression analysis has been successfully implemented on predictive maintenance purposes by Solomentsev et al. (2022), Zaliskyi et al. (2022) and Kuzmin et al. (2019), which strongly suggests segmented regression to be a viable analytics method in the context of pinch valves.

The behaviour described by Solomentsev et al. (2022), is consistent with the hypothesized behaviour of the sleeve during the stress test (Flowrox™ Experts 2023), thus it can be assumed that a similar method to the one developed by Solomentsev et al. (2022), is the method that should be applied to the proposed analytics methods for pinch valves.

7.2 Proposed practical application of developed analytics methods

By combining the methods for filtering and testing of the data presented in the chapters 4 and 5, and translating them into MATLAB-programming language, the data gathered in the test described in chapter 6, can be easily analyzed and the desired parameters examined.

The sub-question one can be answered with the ”CLOSING FORCE” section of this program, shown in the figure 13 of appendix A. This part of the program gathers the cylinder pressure data and calculates closing forces automatically. The closing force data is then filtered as described in section 4.1. After the filtering, the segmented regression models are fitted into the data. The length of the period examined for wear-out can be easily modified. Using this program, any abnormal changes in closing force during the test can be visually detected by the model slope coefficients.

The sub-question two can be answered with the ”POSITION DEVIATION” and ”POSITION DEVIATION FOR CAVITATION” sections of this program, shown in the figure 13 and 14 of appendix A. These parts of the program calculate the deviation automatically from the position data. In the first section, the segmented regression models are fitted into all of the data, in order for any abnormal changes to be detected. In the second section, the data is additionally filtered for conditions where cavitation can happen. Using these sections, any abnormal changes in the position deviation can be detected visually.

As this program translates the data from the positioner, into values that can be used to visually determine whether the changepoint has been reached, it is considered to answer to the main research question.

7.2.1 Analysis of the results, possible improvements and future research

Due to limitations in the scope of the research, time and laboratory resources, the methods proposed are not a finished product ready for implementation, but rather a tool to prove a concept. To further evolve the program closer to its final form, especially considering the implementation to the positioner, some improvements are suggested:

The assessment of the functionality of the analysis program is based heavily on the theoretical hypothesis of the sleeve’s behaviour, and preliminary data from the stress test. Thus, further research is required to establish, with absolute certainty, the applicability of the results, most notably considering the implementation to valves across the model range. However, as the construction and working principles remain largely unchanged, the results for the closing force and simple position target deviation found in this thesis will provide credible source for direction, considering the possible continuation of research. For cavitation, the viability of the methods must be confirmed with further testing, as cavitation is considerably more likely to occur with sleeves of larger diameter.

Due to the positioner naturally being unable to perform visual analysis, the method for determining whether one of the data sets is past its wear-out changepoint, should be a numerical comparison of the linear model coefficients. In this phase of the research, this numerical comparison is not implemented into the program. Data from multiple tests is required to set a value for the amount of difference required to determine, that the changepoint has been passed and the sleeve will fail. For those reasons, the difference of the coefficients must be determined visually, until the triggering values for the decision-making body can be set based on data. For the time being, the collection of the data is still dependent on laboratory testing. For that reason, manually importing the data and visually determining the changepoint are sufficient methods to continue research.

Additionally, the slow transfer speed of HART presents problems with the analysis through the diagnostic log. As the HART signal is only received every second, often the update occurred outside of the desired window, especially with the examination of closing force data. However, should the feature eventually be implemented into the positioner, these problems could be avoided as the positioner is much more capable with data handling within its own software.

8 SUMMARY

This chapter concludes and summarizes the information gathered in this thesis. No previous research has been conducted at Valmet Flow Control for the opportunities offered by analyzing the data from the ND9000-positioner. As is evident by the results of this thesis, maintenance analytics methods can be applied with the positioner's data, to analyze it for the event of the sleeve breaking. From earlier literature, segmented regression has been identified to be a method that is viable for use in the context of a pinch valve's positioner. Should the sleeve's construction fail in a way consistent with the hypothesis by Flowrox™ Experts (2023), the changepoint in the data should be predictable using the analytics methods proposed. By how much in advance this prediction can be made, will depend on the circumstances and should be studied during future research.

The practical application in the form of the cyclic stress test and the analysis program, acting as methods to determine whether the event of the valve's sleeve breaking can be seen in the diagnostic data have been developed, thus the aim of the research has been achieved. As this research has been a first step into the field, although further improvement should be conducted once data is gathered, the analysis program is a viable tool to determine, whether the research should be continued in the future. As long as the hypotheses have been correct, the analysis program should act as a proof-of-concept, indicating that the data is valuable. If this shall be the case, it is indicated that its use with Flowrox™ pinch valves should be explored further.

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A APPENDIX: MATLAB analysis test program

The MATLAB analysis program written. Please note: variables ”c1”, ”c2” and ”pos” must be manually created into the .mat workspace file by copying and pasting the data from the table, created by importing the positioner log file’s data. The variables ”c1” and ”c2” correspond to the pneumatic actuator’s front and back end pressures respectively. The variable ”pos” is an nx2 matrix containing both the target position and actual position values, with target position in column one, and actual position in column 2. This must be done manually as MATLAB does not allow multiplication to a single column of a table file.

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```
vars = {'xd2', 'a', 'Aback', 'Afront', 'app1', 'app2', 'approxcf', 'approxd1', 'approxd2', 'b', 'datacf', 'datad1', 'datad2', 'dcyl', 'dev', ↙
'devc1','devc2','devct', 'drod', 'eqcf', 'eqd1', 'eqd2', 'f1', 'f2', 'fitobject','fres', 'n', 'rcyl', 'rrod', 'vars', 'xacf', 'xad1', 'xad2', 'xcf', 'xd1'};
clear (vars{:}); %clearing variables

%%%%%%%%% CLOSING FORCE %%%%%%%%%

a=1; %setting a running counter variable
app1 = 1000; %apporximation length

dcyl = 100; %actuator piston diameter, mm
drod = 36; %actuator piston rod diameter, mm

rcyl = dcyl/2; %piston radius, mm
rrod = 36/2; %piston rod radius, mm

Afront = ((pi)*rcyl^2)-((pi)*rrod^2); %cylinder front end effective area, mm^2
Aback = ((pi)*rcyl^2); %cylinder back end effective area, mm^2

f1 = 0.1*c1*Afront; %calculate front end closing force, N (Mpa*mm^2, 0.1*1 bar = 1MPa)
f2 = 0.1*c2*Aback; %calculate back end closing force, N

for n = 1:size(pos,1)
    if (pos(n,2))>94 && ((pos(n+1,2))>(pos(n,2)) || (pos(n+1,2))==(pos(n,2))) %check for desired position
        fres(a,1)=(f2(n,1)-f1(n,1));%if true calculate and add the corresponding resultant force to vector fres
        a=a+1;
        n=n+1;
    else
        n=n+1; %if not skip
    end
end

xcf = linspace(1,size(fres,1),size(fres,1))'; %x-axis
xacf = linspace(size(fres,1)-app1,size(fres,1),app1); %approximation x axis
xacf = transpose(xacf); %transposing to a vertical matrix

eqcf = fittype('poly1'); %define the equation of fitted model
fitobject = fit(xcf,fres,eqcf); %fit model to pressure data

datacf = fitobject(xcf); %calculation
approxcf = fitobject(xacf);

subplot(3,1,1);
plot(xcf,fres,".",xcf,datacf,"-",xacf,approxcf,"--"); %plot pressure values and model

%%%%%%%%% POSITION DEVIATION %%%%%%%%%

dev = abs(pos(:,1)-pos(:,2)); %calculation of deviation

a=1; %setting a running counter variable

app2 = 1000; %apporximation length

xd1 = linspace(1,size(dev,1),size(dev,1))'; %x-axis
xad1 = linspace(size(dev,1)-app2,size(dev,1),app2); %approximation x axis
xad1 = transpose(xad1); %transposing to a vertical matrix

eqd1 = fittype('poly1'); %define the equation of fitted model
fitobject = fit(xd1,dev,eqd1); %fit model to pressure data

datad1 = fitobject(xd1); %calculation
approxd1 = fitobject(xad1);

subplot(3,1,2);
```

Figure 13: MATLAB analysis test program, page 1

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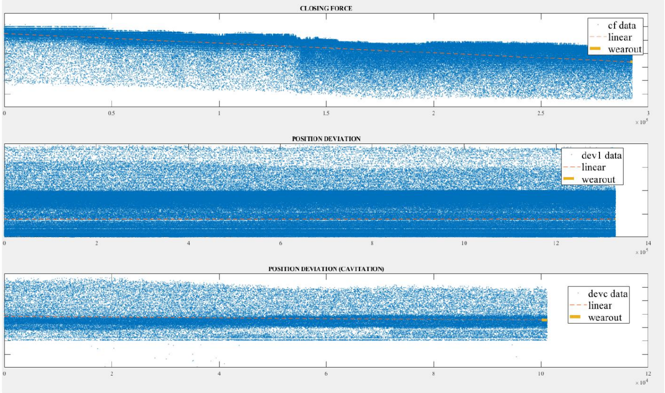
```
plot(xd1,dev,".",xd1,datad1,"-",xad1,approxd1,"--");

%%%%%%%%% POSITION DEVIATION FOR CAVITATION %%%%%%%%%

dev = abs(pos(:,1)-pos(:,2)); %calculation of deviation

a=1; %setting a running counter

app2 = 1000; %apporximation length

for n = 1:size(dev,1)
    if (pos(n,2))>94 && (pos(n,2))<98 %check for desired position
        devc1(a,1)=(dev(n,1));%if true calculate and add the corresponding resultant force to vector devc1
        devc2(a,1)=(0);
        a=a+1;
        n=n+1;

    elseif (pos(n,2))>84 && (pos(n,2))<94 %check for desired position
        devc2(a,1)=(dev(n,1));%if true calculate and add the corresponding resultant force to vector devc12
        devc1(a,1)=(0);
        a=a+1;
        n=n+1;
    else
        n=n+1; %if not skip
    end
end

devct = abs(devc1-devc2);

xd2 = linspace(1,size(devct,1),size(devct,1))'; %x-axis
xad2 = linspace(size(devct,1)-app2,size(devct,1),app2); %approximation x axis
xad2 = transpose(xad2); %transposing to a vertical matrix

eqd2 = fittype('poly1'); %define the equation of fitted model
fitobject = fit(xd2,devct,eqd2); %fit model to pressure data

datad2 = fitobject(xd2); %calculation
approxd2 = fitobject(xad2);

subplot(3,1,3);
plot(xd2,devct,".",xd2,datad2,"-",xad2,approxd2,"--");
```



PRELIMINARY DATA AND RESULTS, VALUES CONTAINING PROPRIETARY INFORMATION HIDDEN

Figure 14: MATLAB analysis test program, page 2