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FAILURE ANALYSIS OF HYDRAULIC PUMPS

Bachelor's Thesis
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ABSTRACT

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Hydraulic pumps are one of the main components in many different kinds of heavy machinery such as excavators and forest machines. The main function of the pump is to generate flow for actuators, in which case its failure affects the operation of the machine considerably. Because some of the failures could be prevented if those could be predicted, it is crucial to know how the pumps are failing and what effects those have. This work will examine how hydraulic pumps fail as well as what their causes and effects are. Also, the most common analysing and diagnosing techniques are briefly looked into.

In the first part of the literary research, the failure modes of the pumps are presented, as well as their causes and effects. The latter section presents the most common techniques used in analysing and diagnosing the failures.

Literary research shows that the causes of failures can be divided into four categories. Most of the failures occur due to factors originating from operation and maintenance and the largest factor is the improper or contaminated hydraulic fluid in the system. Because of this, the most common failure mode in pumps is the wear of components. Although, there are similarities in faults, the varying structures of the pumps cause several differences in the failures. The most common effects of failures are abnormal vibrations and increased noise.

Techniques used in analysing and diagnosing hydraulic pumps vary depending on the purpose, possible requirements for further investigation, and of the faults investigated. Most techniques used in analysing include at least the fault, its possible causes and effects. If needed the analysis can also include the seriousness of the failure, occurrence, and determination.

Current diagnosing techniques are mainly signal-based and focus on failures occurring individually although the simultaneous occurrence of multiple failures is possible. Due to this, in the future diagnosing concurrent failures would be beneficial.

Keywords: hydraulic pump, failure mode, failure analysis, failure diagnosis

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Elina Vuorinen: Hydraulipumppujen vikaantuminen
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Hydraulipumppuja käytetään useimmissa työkoneissa, kuten kaivureissa ja metsäkoneissa. Pumpun tehtävänä on tuottaa virtausta toimilaitteille, jolloin sen vikaantuminen vaikuttaa koneen toimintaan huomattavasti. Koska osa näistä vioista voitaisiin estää, jos ne pystyttäisiin ennustamaan, on erityisen tärkeää tietää miten pumput vikaantuvat ja mitkä ovat niiden seurauksia. Tässä työssä tutkitaan miten hydraulipumput vikaantuvat sekä mitkä ovat niiden syyt ja seuraukset. Myös yleisimmät analysointi- ja diagnosointitekniikat käydään läpi.

Ensimmäisessä osassa kirjallisuustutkimusta esitellään pumppujen vikaantuminen sekä niiden syyt ja seuraukset. Jälkimmäisessä osassa esitellään yleisimpiä tekniikoita, joita on käytetty vikojen analysointiin ja diagnosointiin.

Kirjallisuustutkimus osoittaa, että vikojen syyt voidaan jakaa neljää ryhmään. Suurin osa vioista johtuu huollosta ja käytöstä peräisin olevista tekijöistä ja suurimmaksi yksittäiseksi tekijäksi nousi hydraulijärjestelmässä käytetty neste ja sen likaantuminen. Tämän takia kaikista yleisin vika pumpuissa on osien kuluminen. Vaikka vioissa on useita yhtäläisyyksiä, pumpun rakenne aiheuttaa monia eroavaisuuksia vikoihin. Vikojen yleisimpiä seurauksia ovat pumpun erilaiset värähtelyt ja äänitason muutokset.

Analysointi- ja diagnosointitekniikat, joita käytetään hydraulipumppujen kohdalla vaihtelevat riippuen analysoinnin tai diagnosoinnin tarkoituksesta, mahdollisista vaatimuksista jatkotutkimuksia varten ja tutkituista vioista. Useimmat analysoinnissa käytetyt tekniikat sisältävät vähintään vian, sen mahdollisten syiden ja seurauksien tutkimisen ja analysoinnin. Tarvittaessa analysointi voi sisältää myös vian vakavuuden, ilmenemis- ja määritystiheyden.

Tämänhetkisistä diagnosointitekniikoista suurin osa on signaalipohjaisia ja ne keskittyvät pääasiassa yksittäin tapahtuviin vikoihin, vaikka useiden vikojen samanaikainen ilmeneminen on mahdollista. Tästä johtuen olisi hyödyllistä kehittää diagnosointitekniikoita useiden samanaikaisten vikojen diagnosointiin.

Avainsanat: hydraulipumppu, vikaantuminen, vian analysointi, vian diagnosointi

PREFACE

I want to thank my supervisor Tatiana Minav for giving me great feedback throughout the writing process and helping me to do my best. I would also like to thank the members of Zonal Hydraulics – research group for their support and feedback.

Tampere, 8 May 2021

Elina Vuorinen

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LIST OF SYMBOLS AND ABBREVIATIONS

ARPD	Average Relative Power Difference
FFT	Fast Fourier Transformation
FMEA	Failure Mode and Effect Analysis
RPN	Risk Priority Number

1. INTRODUCTION

Hydraulic pumps are used in various applications, for example in non-road mobile machinery, such as excavators and mine loaders. The hydraulic pump has a major significance in the machines as it provides flow to actuators in the system. If a hydraulic pump fails, in the worst-case scenario, it can cause the machine to shut down or break. Due to the effects a failed pump has on the system, proper maintenance and data management are crucial [1]. Changing a failed pump to a new one can be expensive [2] and therefore cause unnecessary downtime and cost for the company.

To decrease or prevent downtime of hydraulic machines, it would be important to detect the possible failure of critical components such as the pump. This would keep the overall efficiency of the pump as close to the maximum value as possible [3] and decrease maintenance costs. Another problem a pump failure might cause, is decreased operational safety of the people working in the immediate proximity of the machine [4].

The scope of this thesis is limited to pump failures in positive displacement pumps, including axial piston, external gear, and vane units. The pumps included in this thesis are commonly used in mobile machinery and aircrafts. This work will concentrate on oil hydraulics applications; therefore, water pumps are not included in the scope of the work. Analysing and diagnosing techniques are limited to the most commonly used including a few examples of established techniques.

The goal of this literature research is to explore how axial piston, external gear, and vane pumps fail. To understand these failures, it is important first to know what is causing all of these failures. And because the hydraulic pump is one of the main components in a hydraulic system, the effects of failures will also have an impact on the operation of the system. Due to these factors also causes and effects of occurring failures are looked into in this work. The common techniques to analyse and diagnose these failures are also explored.

The structure of this thesis consists of the following sections. The first section will provide the common causes of failures of pumps. The second section of this work explains the failure modes and their effects on three different pump types. The third section explains analysing and diagnosing failures in general. Then the subsections include examples of analysing and diagnosing techniques. Conclusions of the thesis are stated in the last section of the thesis. Appendix A contains explanations for terms used in this thesis.

2. CAUSES OF PUMP FAILURE

To properly understand pump failure, it is necessary to study the cause of failure. Because pumps are used in a variety of applications, factors such as working environment, maintenance, fluid pressure, and different working loads can eventually influence the pump.

It is possible to prevent failures that reoccur if the failure mechanisms can be determined and preventive maintenance procedures can be made in advance. Preventative actions are not always possible to take, for instance when failure is not recurring or due to lack of time, as studying the causes takes time and effort. Usually, only the causes of the most critical failures are identified. [5, pp. 467]

Pump failures can have many different sources, such as operation and maintenance, installation, design, and manufacture. The failure frequency of these sources can be seen in Table 1. Based on root-cause analysis, the most common sources of failures are improper operation and maintenance. Root causes are the initial causes, which can lead to intermediate and proximate causes, and finally to failure mechanism and mode. Based on research, 85–95 % percent of pump failures happen because of foaming and aeration, cavitation, contamination, fluid oxidation, over pressurization, and/or improper viscosity. [5, pp. 473]

Most of these failure causes can be connected to fluid, making it one of the most common causes of failure in hydraulic pumps. Often these causes are connected to viscosity or contamination of the fluid. Contamination can cause up to 70–80 % of failures in hydraulic systems [6].

***Table 1** Sources of failures. Adapted from* [5, pp. 463]

Source of failure	**Failure Frequency (%)**
Operation and maintenance	80
Installation	12
Design	6
Manufacture	2

Therefore, with proper design, maintenance, and operation most failures can be prevented or delayed. Besides these factors, also proper filtration and fluid, suitable thermal stability, and adequate knowledge of hydraulics will increase the lifetime of the pump [7].

The causes of pump failures can be classified according to the criticality and importance of the failure mode, depending on the analysis technique used. As many pump types have different structures also the causes and thereby failures vary. These factors will be covered in the following sections.

3. PUMP FAILURE

This section explains failure mode and presents failure modes and effects for three commonly used hydraulic pumps. Section 3.1 explains the term failure mode, sections 3.2, 3.3, and 3.4 focus on failures in axial piston, external gear, and vane pumps respectively.

3.1 Failure Mode

Hydraulic pumps have multiple different failure mechanisms and modes due to various constructions, changing working conditions, and alternating maintenance levels. Also, the severity and occurrence will vary depending on the pump type and the failure mode. When identifying the causes and the effects pump failure has on the system, it is common to also identify the failure mode.

The failure mode explains the fault and how it is presented in the component, meaning the way the component is not able to perform its function or doesn't fulfill its specifications [5, pp. 466]. Because each component has its own characteristics, such as environment, function, and quality, the failure mode is property inherent to each item.

The failure modes can be divided into two types, functional and structural, depending on what is being focused on. The functional approach focuses on the function of the item and the structural approach requires more information about the fault. Therefore, functional is a more qualitative approach than structural approach is. Regardless of the approach, it is important to have a good understanding of the components and the function as analysis is based on those. [5, pp. 466–467]

The effects of failure are dependent on the failure modes as those can happen in different areas of the pump. Based on research the most common effects of pump failures are increased noise and abnormal vibrations. Other common effects are decreased volumetric efficiency, excessive heating, leakages, and pressure changes in the system.

3.2 Failures in Axial Piston Pump

Swash plate type axial piston pump consists of several components including driveshaft, swash plate, slippers, pistons, valve plate, and housing. Details of the structure can be seen in Figure 1. In an axial piston pump, the pistons (4) are in cylindrical holes inside the rotating cylinder block (5). As the driveshaft (1) rotates the cylinder block, the angled swash plate (2) causes the pistons to move back and forth in the holes. This way the fluid at the inlet port (9) is sucked to the cylinder block's holes by retracting pistons and at the outlet port (10) the piston extracts and forces the fluid to move to the outlet. The volumetric displacement is defined by the swash plate, which is either rotary or stationary, as it is controlling the length of the piston strokes. [5, pp. 21–22] As the angle of the swash plate increases the provided flow increases, and as the angle decreases also the flow decreases [8]. In an axial piston pump, proper lubrication is important and as lubrication causes continuous leakage, the pump requires a port for external drainage.

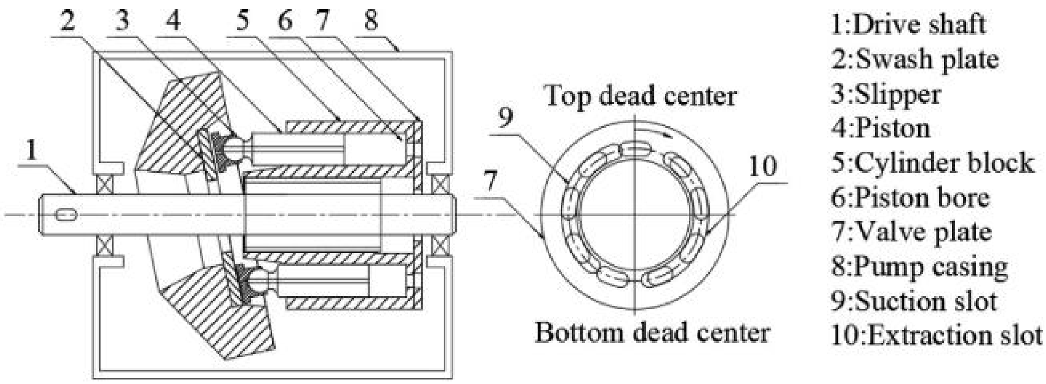


Figure 1 *Piston pump* [4]

Due to the structure of axial piston pumps which is seen in Figure 1, it has several components in sliding contact and therefore, are prone to leakages and wear. Because of that, wear is a common failure mode and it can be detected between the components in sliding contact called friction pairs, which are the valve plate and cylinder block, and the piston and cylinder wall. [5, pp. 470] Based on research on the topic, 80 % of failures in axial piston pumps are caused by wear [9]. Therefore, a lot of research has been conducted and multiple friction pairs have been analysed. Figure 2 lists common failure modes, causes, and effects in axial piston pumps.

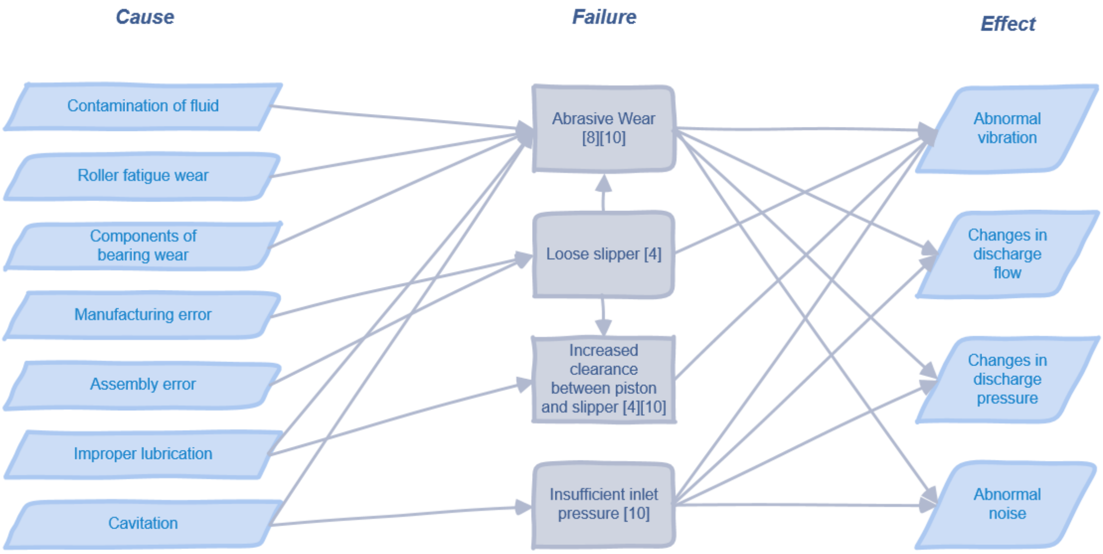


***Figure 2** Possible failure modes, causes, and effects in the axial piston pump*

The type and degree of wear are dependent on the friction pair studied. Wear can result in internal leakages, which will lead to decreased outlet flow and volumetric efficiency. [9] Besides leakages, wear can shorten the service life of the pump. The problem with identifying the factors that influence wear and predicting its status is the lack of real-time measurements of wear masses [10].

Shown in Figure 3 is the most common failure mode, abrasive wear. Abrasion of valve plate covers 38 % of failures in piston pumps used in aircrafts. Causes of this failure include contamination of the fluid, wear on different parts of the pump, cavitation, and poor lubrication. The effects of the failure mode are increased overall leakages, decreased volumetric efficiency, abnormal vibrations, and abnormal noise. [11]

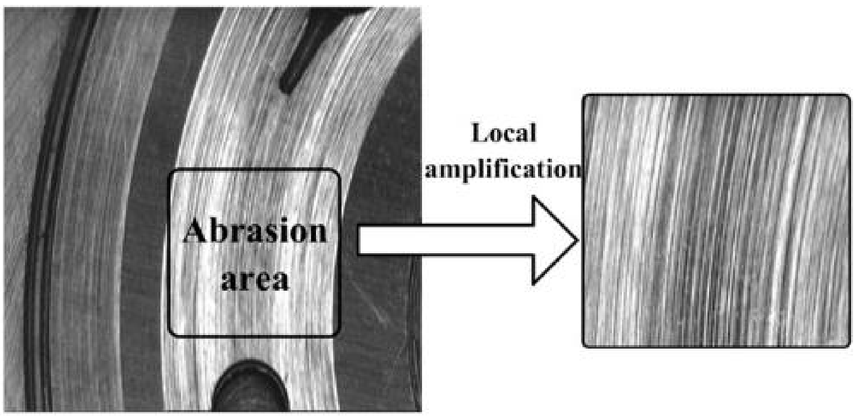


***Figure 3** Abrasion of valve plate* [11]

One of the friction pairs analysed is the swash plate and slipper. According to [10] several parameters, including fluid temperature, thermal capacity, velocity, possible contaminants, lubrication, and load, influence wear behaviour. The biggest factors affecting the sliding motion are oil film thickness and lubrication between the friction pair. At the same time, several factors such as outlet pressure, the temperature of the fluid, and the rotational speed of the pump can substantially affect the oil film thickness.

For instance, as the fluid temperature rises, also the wear rate will increase. Outlet pressure has similar effects as the temperature on the wear behaviour, meaning increased outlet pressure increases the wear rate. The outlet pressure will affect the load impacting the slipper pair, but it can also have an effect on the oil film thickness and conclusively affect the wear rate. The third factor, rotational speed, affects the oil film thickness and the strokes of friction in the unit interval will vary depending on the rotational speed. Only the effect of rotational speed on wear rate was considered in the study conducted by Ma et al. [10]. With the rotational speed increasing the wear rate decreases, especially with high rotational speeds. The main reason for this decrease in wear rate is the increased oil film thickness caused by increasing rotational speed. [10]

Another common failure is a loose slipper failure. In normal working conditions, a gap between the piston (4) and the slipper (3) should be sustained. Manufacturing and assembly errors will cause an increased wear rate between the piston head and the slipper. Due to this wear caused by a loose slipper, the clearance between piston and slipper increases, which causes abnormal vibration. As the energy of the vibration signal increases the seriousness of the failure will also increase. [4] Other causes for increased clearance between piston and slipper, besides wear, are repetitive loads during operation or insufficient lubrication between the piston head and slipper [11].

According to Du et al. [11], five main types of faults in aircraft axial piston pumps, which include the mentioned failure modes, abrasion of the valve plate, increased clearance between piston and slipper, and in addition, roller bearing wear, insufficient inlet pressure, and swash plate eccentricity. In Figure 4, roller bearing wear can be noticed. One cause for this failure mode is roller fatigue wear and the effect of the failure is abnormal vibration in the radial direction.

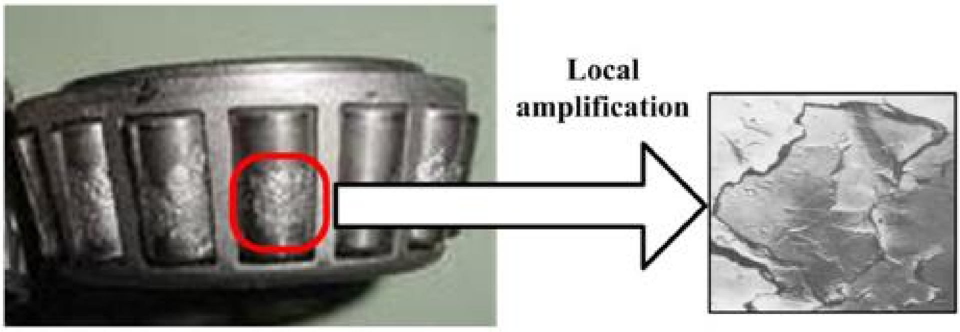


Figure 4 *Roller bearing wear* [11]

Insufficient inlet pressure can be caused by cavitation inside the pump, by too thin inlet pipe, broken tank pressurizer, or low liquid level combined with high pump velocity. In the system, the failure manifests itself as vibrations, oscillating discharge pressure and flow, and abnormal noise. The swash plate eccentricity is caused by either assembly error or serious wear on side of the swash plate. This failure mode also causes abnormal vibrations.

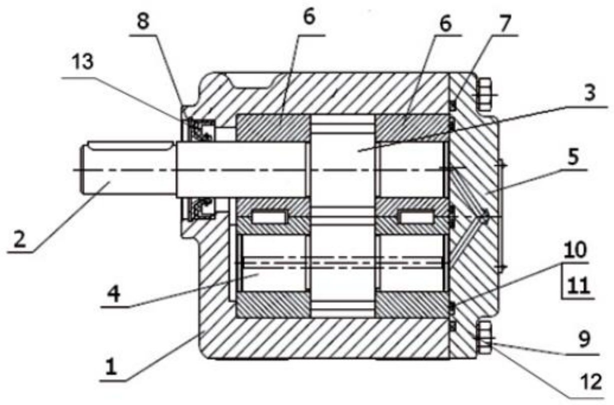
Another common failure in the variable displacement axial piston pump is the looseness of the regulator valve spring. Because the pump's discharge pressure is defined by the spring's preload calibration, the regulator valve spring's looseness can lead to decreased pressure from the pump [8]. Because of that, this failure mode can be noticed from discharge pressure data when there is no load.

Other common failure modes in axial piston pumps are roller-bearing fatigue, valve-plate scoring and erosion, and slipper-pad failures [5, pp. 418]. Cavitation is also one of the possible failure modes that can occur in axial piston pumps due to, for example, foaming and aeration. Cavitation causes noise and abnormal vibration in the pump.

3.3 Failures in External Gear Pump

One of the most commonly used hydraulic rotary pumps are gear pumps, therefore, a considerable amount of research has been conducted. Gear pumps often operate in demanding conditions, for example, in high temperatures and high working pressures [12]. It is robust, sturdy, and not sensitive to variation in viscosity or contamination of the hydraulic fluid.

The gear pumps can be divided to internal and external from the construction point of view. The external gear pump is one of the most commonly used in off-road machinery. The external gear pump consists of a pair of gears (3,4), housing (1,5), and side plates. Inside the housing, the gears are mounted on shafts (2), which are held by needle bearings (6) in the housing. One of the gears (3) is driven by the driveshaft (2) and the other gear (4) rotates freely. As the gears rotate, fluid is trapped between the gears and housing moving it from the inlet port to the outlet port. External gear pumps have fixed displacement. [5, pp. 17–18] Figure 5 illustrates simplified schematics of an external gear pump.



1. Body
2. Driveshaft with key
3. Drive gear
4. Driven gear
5. Cover
6. Bearing
7. Sealing ring
8. Shaft sealing ring
9. Screw
10. Sealing ring
11. Sealing ring
12. Spring washer
13. Spring ring

Figure 5 *External gear pump* [12]

According to [13], in gear pumps, various factors can affect the failure such as temperature, speed, the viscosity of the fluid, and load. Moreover, pressure and external forces, which are directed to the pump or its shaft, can cause a failure. Most of these factors are connected to operation and maintenance, which is aligned with the information listed in Table 1.

While investigating pump failure, the components of the pump that are seen in Figure 5, such as pump housing, bearing, and seal of rotational elements are crucial for the operation. The reasons for this are the working conditions, high pressures, and high rotational speeds of gear pumps.

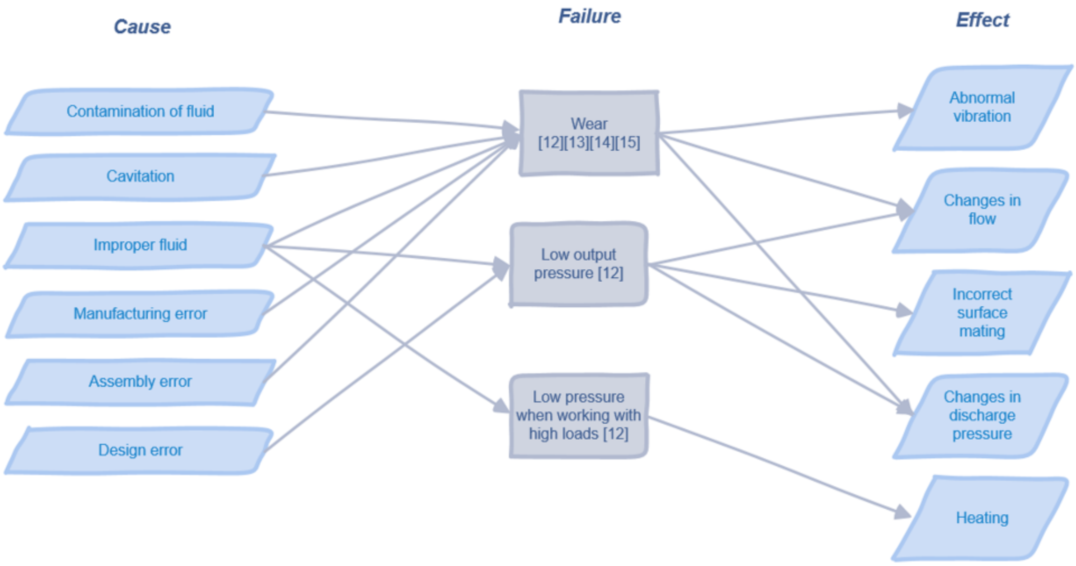


Figure 6 *Possible failure modes, causes, and effects in the external gear pump*

Based on research on gear pump failures, in approximately 60 % of failed pumps, gears are the main cause of failure [14]. Figure 6 presents the most common failure modes, causes, and effects that occur in external gear pumps during operation.

Some factors causing gear-based failures are pump operation and working fluid [12][14]. Although gears are the most commonly affected, those are not the only components in an external gear pump that might fail [14].

One of the most common failure modes in gear pumps is wear. This is mainly because of the structure of gear pumps, as the meshed gears are in constant use and due to that prone to wear if the lubrication is improper. Also due to the structure, the surface of the gear tooth bears large pressure for the gear transmission system, which eventually leads to wear of the tooth surface [15].

Wear can be divided into two different types: abrasive and adhesive. Abrasive wear, also known as abrasive removal of surface material, is caused by contaminants in the fluid, which can be a consequence of a broken in-line filter [13]. Another reason for wear is poor maintenance, which would appear in the system as improper fluid or low quality of fluid, also manufacturing errors can also be the reason for wear. Because the hydraulic fluid is spread all over the pump, gears are not the only components in the gear pump that are prone to wear due to improper fluid, also side plates and bushings are prone to wear.

Besides wear, a failure mode in a gear pump can be, for example, low output pressure, or low fluid pressure out when working at high loads. The symptoms of low output pressure are incorrect surface mating, an uneven turning of the gears, or slow turning of the gears. Depending on the symptom, the cause can be a design error, bearing failure, bearing shaft failure, or too low viscosity. If this failure mode occurs, it will cause uneven flow and minor pressure leaks. The symptom of low fluid pressure out when working at high loads is excess heating of the hydraulic fluid and it is caused by improper hydraulic fluid, which has low viscosity at high temperatures. [13]

Other common failure modes in gear pumps are roller-bearing fatigue, gear-tooth surface pitting and fatigue, seal-plate scoring, and seizure [5, pp. 418]. Besides the failure modes mentioned so far, several component failures can occur in external gear pumps during operation. These failures include thermal, corrosive, and fretting fatigue, and cavitation corrosion.

Based on the analysis by Lisowski and Fabiś [16], the most likely component failures during transfer were defined. These failures were bending deformation, impact fracture, abrasive wear, and adhesive wear. Failures that were considered to happen occasionally were pitting corrosion and cavitation corrosion. The most uncommon failures included buckling, known as deformation of the structure caused by force, brinelling, known as indentation forming on hard surfaces, erosion, meaning cutting of material by hard particles, blistering and different kinds of fatigue.

3.4 Failures in Vane Pump

The vane pump consists of a cam ring (10) and inside that is a cylindrical rotor (11) connected to a driveshaft (5) and sliding vanes (13) in rotor grooves. Port plates (9,14) seal the sides of the rotor and vanes. Pump operation is based on the volume between the rotor and the cam ring changing during rotation. In the first half of rotation, the volume increases forming suction and on the second half the volume decreases, and the fluid is ejected to the outlet port. Vane pumps can be either fixed or variable displacement depending on the eccentricity of the rotor. [5, pp. 19–20] Figure 7 shows an exploded view of a double vane pump, which shows all of the components inside a vane pump.

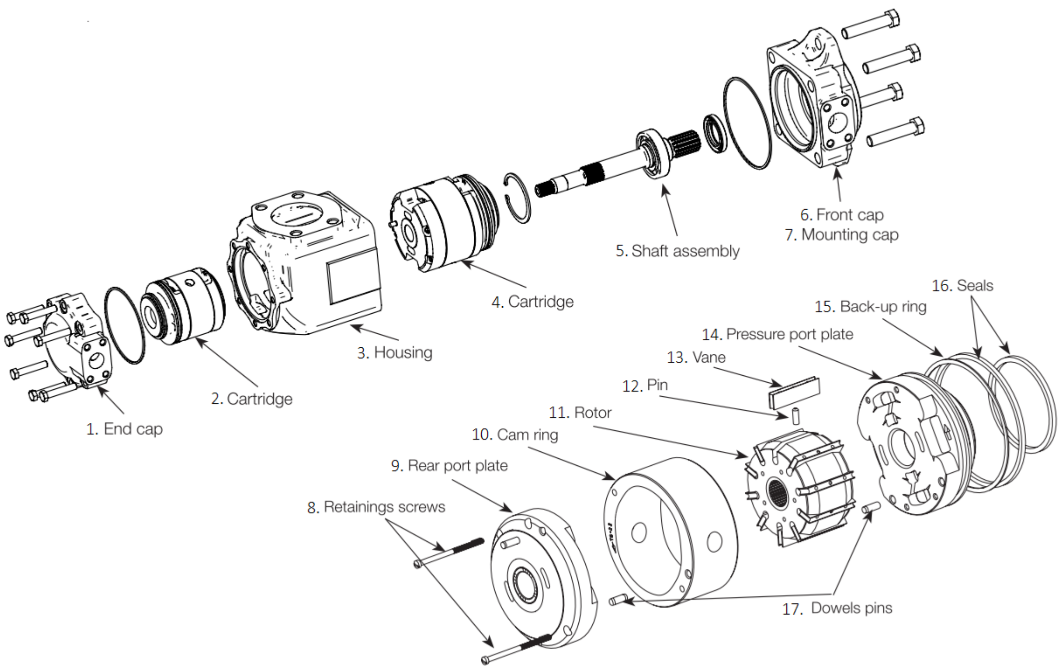


Figure 7 *Double vane pump. Adapted from* [7]

Due to the construction of vane pumps, there are several components in sliding contact, including vane-on-cam ring surface. This means improper lubrication is a common source of failure. [5, pp. 470] And due to the importance of lubrication and fluid, 80 % of failures in vane pumps can be linked to fluid contamination [7]. A few of the causes of these failures can be, for example, cavitation, aeration, foaming, or contamination. In vane pumps, the common failure modes include wear of components, shaft (5), vane (13), and port plate (9,14) problems, and cavitation. These faults, their causes, and effects are presented in Figure 8. Besides shaft, vanes, and port plates, the vane pump has several other components that might suffer a mechanical failure.

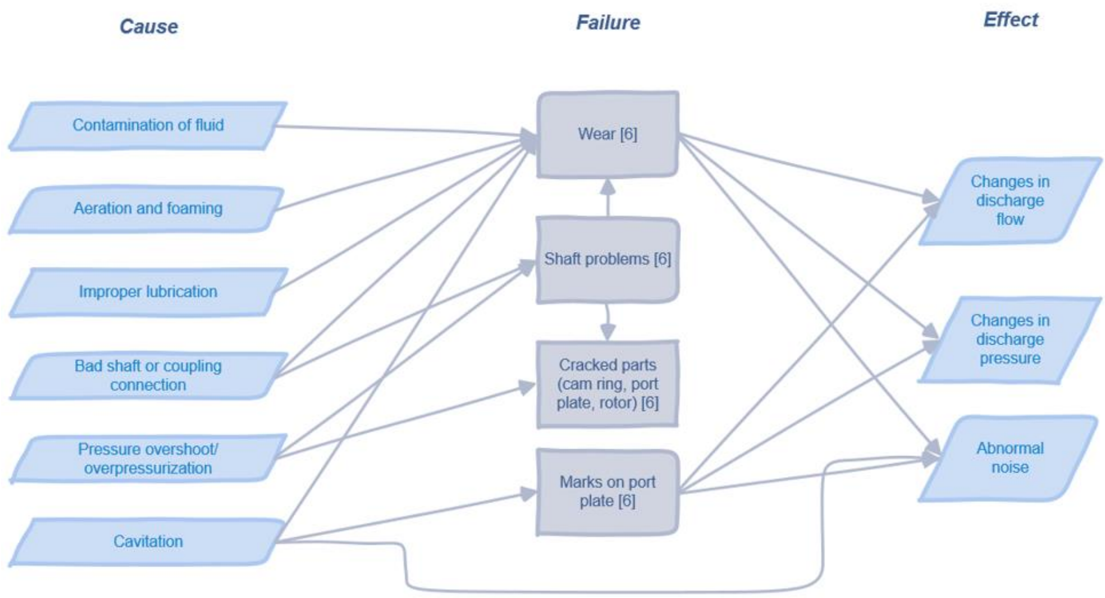


***Figure 8** Possible failure modes, causes, and effects in the vane pump*

A common failure mode in vane pumps is wear and it appears mainly as severe vane and ring, port plate, bearing, and cavitation wear [5, pp. 418]. In most of the mentioned cases, the wear is caused by improper lubrication or contamination, mainly solid particle contamination. On port plates (9,14), the cause of wear can also be unbalanced operation due to aeration and foaming. This will increase the level of noise and cause changes in output flow and pressure. The wear in other parts, such as splines and key, can be caused by a bad shaft or coupling connection. [7]

Failures with vanes (13) include the wear mentioned earlier, which is caused by solid contaminants, and failures caused by water contamination [7]. The latter will cause deposits to form on the vanes and because of that, deteriorate the mechanical efficiency of the pump. It can also cause foaming which will cause vanes to destabilize and this will generate ripples and sharp vane lips edges. In the system, this failure can be noticed as high noise level and deteriorated pressure capabilities.

Shaft (5) problems can have multiple different failure modes, such as fretting, fretting corrosion, seen in Figure 9, bushing, cam ring markings, seen in Figure 10, seal problems, and shaft rupture [7]. The cause of shaft rupture is either a bad shaft or coupling connection. In the worst-case scenario, the shaft of the pump can be broken by instant pressure shoot. At the same time, it can crack the cam ring (10), cut dowel pins (17), but also crack or rupture the pressure port plate (14) or rotor (11).

Figure 9 *Fretting corrosion (5)* [7]

Figure 10 *Marked cam ring **(10)*** [7]

Like vanes and shaft, also port plates (9,14) have several failure modes besides the faults mentioned already. Erosion and scars on port plates might occur if the viscosity of the fluid used is too low or if cavitation occurs. Also, high temperature and scarring on the rotor of the pump can appear due to low viscosity. One failure of the pressure port plate (14) is a deflection of it. This is caused by cycled over pressurization, which is also causing fatigue and deflection of the cam ring’s external diameter. [7] These failures caused by mechanical and improper pressure often cause failures related to broken pump components and thus are more severe compared to faults caused by contaminated or improper fluid in the system. One cause of problems on port plates is cavitation as it can cause rotor and port plate seizure. Another failure caused by cavitation is marks on the port plate, which causes unusual noise and changes in the output flow. It can also appear as no pressure in the system.

As a failure mode, cavitation can be due to aeration and foaming or that the pressure gradient is too high. It will appear as a high noise level, erosion of pins (12) and vanes. Other than erosion, the pump cavitation can cause ripples on the cam ring and twisted torsional rupture of the shaft. [7] Improper viscosity can also cause cavitation or erosion depending on the viscosity being too high or too low. Effects of these are no flow and high temperature respectively.

Besides the failure modes mentioned earlier, other possible mechanical failures in vane pumps include improper positioning of dowel pins (17), improperly mounted cartridge screws, and loose fasteners. Effects of these faults include unusual noise, unstable output flow, no output pressure, and cavitation. The fluid-borne problems depend on the causes. Improper bleed-off can lead to abnormal working of the pump, unusual noise, or overheating if the pump has not been properly lubricated. Other causes include improper fluid and grease. [7]

3.5 Summary

Even though different pumps have diverse structures and working mechanisms, the failure modes have a few similarities. In hydraulic pumps, the most common failure is wear of the components and because it is often caused by improper fluid, low quality of fluid, improper operating conditions, or cavitation, it is not specific to a certain pump type. Frequency of wear does have variation, for example in axial piston and vane pumps, the working fluid has bigger importance than in gear pumps as their structure is more prone to failures caused by improper fluid and lubrication. Other failures that are not specific to a pump type, are the misalignment of the shaft, bearing failures, the fatigue of components, and cavitation.

In most cases, the hydraulic fluid is the cause of failure. It can be improper viscosity, improper lubrication, aeration and foaming, or contamination of the fluid. Common effects of failure modes in these pump types are increased noise and vibration, but also changes in output flow and pressure are often presented with failures.

Although failures are analysed and factors affecting those are identified, the results cannot be generalised to other pump types. This is due to differences in structures and their varying working conditions.

In the following table, Table 2, the most common effects of failures are presented with the failure modes generating them.

Table 2 *Common effects and failure modes causing them*

Effect	Failure mode
Abnormal noise	Insufficient inlet pressure Aeration Cavitation Loose or worn parts Stuck parts (vanes, pistons, etc.)
Abnormal vibration	Wear Loose parts Insufficient inlet pressure
Changes in discharge flow	Wear Low output pressure Marks on pump parts Insufficient inlet pressure
Changes in discharge pressure	Wear Low output pressure Marks on pump parts Insufficient inlet pressure
Overheating	Too high fluid viscosity Too high internal leakage Excessive discharge pressure Low pressure when working with high loads

4. FAILURE ANALYSING AND DIAGNOSING TECHNIQUES

This section covers the most common analysing and diagnosing techniques used for pump failures. Examples of established analysis and diagnosis techniques are presented in the subsections 4.1 and 4.2.

To successfully analyse failure, multiple different techniques have been developed to detect failures and their causes [5, pp. 464]. These techniques are developed at various levels of depth depending on needs. A few of the commonly used failure analysing techniques are Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis, Event Tree Analysis, and Reliability Block Diagram [5, pp. 464][17, pp. 19]. Besides these common techniques, there are several less frequently used, which can be used when the more common techniques are not suitable for the analysis. The similarities of the techniques include the goals of analysis, which are understanding the analysed fault and its connections to effects and other possible failures.

In diagnosing, the majority of current techniques have been developed to detect separately occurring faults when in practice pumps are likely to have multiple concurrent faults [11]. The techniques designed for single faults are difficult and, in some cases impossible, to adjust to multi-fault diagnosing, and because of this, diagnosing multiple concurrent faults is an important part of the failure diagnosis.

When diagnosing faults, factors such as external load and multiple concurrent failures, increase the difficulty to detect and diagnose faults effectively. Multiple simultaneously occurring failures complicate detecting and diagnosing failures because the acquired data covers several fault features and carries a large amount of information. Furthermore, different failures can have similar changes in measured data, such as in frequency [11]. Due to these factors, feature extraction is a crucial step in diagnosing multiple concurrent faults.

Usually, when detecting failures, the data from installed sensors is utilized. Optimal sensors to diagnose faults depend on the pump and the failure type. For example, faults can be detected from data of vibration or pressure sensors. Commonly used sensors, which are used to detect faults include pressure sensors [18][19], flow meters [19], vibration [18], and acoustic emission sensors [18]. The optimal number of sensors varies from one to multiple depending on the failures being diagnosed. For example, failure causing leakages can be detected either with flow or pressure sensors [17, pp. 14–15].

Currently, the techniques used to diagnose faults can be divided into three groups, model-, knowledge-, and signal-based techniques. Model-based techniques require the model to be established before a diagnosis, knowledge-based techniques need a great amount of knowledge to simulate a reasoning process of a wanted model, and signal-based techniques are established on signals from mounted sensors. [20] Based on the completed research review, signal-based techniques are more common in fault diagnosing than model- and knowledge-based techniques.

The signal-based fault diagnosis techniques contain multiple processes, which include signal acquisition, signal processing and feature extraction, feature fusion, and fault pattern recognition. A common technique for signal processing and feature extraction is wavelet transform [18], technique for feature fusion is Kalman filter [8][18], techniques for fault pattern recognition are artificial neural network, fuzzy logic [18][21], and Hidden Markov model [18][22].

The process of commonly used signal-based intelligent fault diagnosis' main phases and the commonly used techniques in them are presented in Table 3.

Table 3 *Process of signal-based intelligent fault diagnosis and main techniques* [20]

Process phase	Main techniques
Signal acquisition	Vibration Noise Pressure Flow Temperature
Signal processing and feature extraction	Singular value decomposition [23] Fourier transform [24] Wavelet transform [25]
Feature fusion	Principal component analysis [26] Linear discriminant analysis Kalman filter [8]
Fault pattern recognition	Artificial neural network Fuzzy logic [21] Support vector machine [23] Hidden Markov model [22]

Choosing the tools for analysing and diagnosing depend on multiple factors [18]. A few of those are available signals, working conditions, system dynamics, and the most importantly the fault being studied. The most fitting algorithm for the studied fault can be chosen based on the mentioned factors. Moreover, factors such as external load affect the dynamic response of pumps, and because of this, the fault diagnosis becomes more difficult [4]. Faults, their causes, and effects can be analysed and studied with the help of FMEA, which can then be utilized in the diagnosing process of the fault.

4.1 Failure Mode and Effect Analysis

Using the Failure Mode and Effect Analysis helps to prioritise the order of faults that need to be investigated. The FMEA can be used to diagnose, correct faults, or improve the quality of the component. The technique aims to diagnose and evaluate the existing and potential failure modes. Also identifying the cause of the failures, identifying the factors that could reduce or eliminate the possibility of failure, and documenting the corrective process are significant aims of the FMEA. [17, pp. 15]

The analysing process of this technique contains multiple sections. In the first section potential failure modes are defined, including how the component could fail, but also the ways the component might fail. After this, the failure modes, and the effects of those will be defined. The next step is defining the potential causes of the failure, which should include all the possible ways how the failure could occur for each failure mode that was defined earlier in the process. [17, pp. 16–17]

After analysing the causes, failure modes, and effects, the controls, which could prevent or detect these failures are studied. In the next phase, the Risk Priority Number (RPN), an indicator telling the severity of the failure, is calculated. The highest RPN indicates the highest priority and significance. RPN can be calculated using the following equation

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}. \qquad (1)$$

In equation (1) severity indicates how seriously the failure will impact pump or system operation, occurrence indicates the frequency of the failure and detection indicates how likely it is to detect the failure.

Depending on the intended use of the FMEA, different sections of it can be used. Different types may include focusing on system, design, service, or process. Even though the use of FMEA varies, most of the FMEA tables include failure mode, cause, and effect. An example of the FMEA table is shown in the following Table 4, which includes the basic sections, failure mode, cause, and effect, of FMEA. Besides these, the RPN was included as it was used in upcoming phases.

***Table 4** FMEA adapted from* [11]

Potential failure mode	Potential effect(s)	Sev.	Mechanism(s)	Occ.	Current process controls	Det.	RPN
Abrasion of the valve plate	Pump overall leakage increases, volumetric efficiency decreases, abnormal vibration	5	Damaged lubrication film, mixed lubrication, solid contaminants in the fluid	6	Add filters	4	120
Insufficient inlet pressure	Intermitted violent vibration of the pump, an oscillation of discharge pressure and flow, abnormal noise	7	Pressurizer of tank breaks down, excessively thin inlet pipe, high velocity of the pump and low liquid level of the tank, serious cavitation inside the pump	5	Good assembly	4	140
Roller bearing wear	Abnormal vibration in the radial direction	4	Roller fatigue wear, components of bearing wear	4	Add filters	6	96
Clearance incrementally increases between piston and slipper	Abnormal vibration	3	Repetitive loads on pistons during pump's operation, poor lubrication	4	None	6	72
Swash plate eccentricity	Abnormal vibration	3	Assembly error, serious wear of gaskets on one side of swash plate	4	Good assembly	6	72

According to Du et al. [11], it is possible to have multiple faults occurring in aircraft piston pumps due to the working environment and working loads. Due to most diagnosing techniques being able to effectively diagnose only individually occurring faults they proposed a new technique to diagnose multiple simultaneously occurring faults. Before designing the technique, they analysed five main faults' failure mechanisms and formed the FMEA table seen in Table 4**.** Based on the analysis, sensors, and layout for those were obtained. Optimal sensors for the case are axial and radial vibrations, discharge pressure, and overall leakage flow.

Faults, abrasion of the valve plate, insufficient inlet pressure, and roller bearing wear, were set artificially on the pump to simulate the practical condition of multiple faults occurring simultaneously. The clearances between pistons and slippers were modified by machining to simulate increased clearances. [11]

Table 4 was used by Du et al. [11] to establish a diagnosing technique for multi-fault diagnosis in axial piston pump, which is explained in the next section. The diagnosis utilises the RPNs listed in the table to determine the order of failures to be diagnosed in.

4.2 Layered clustering multi-fault diagnosis

To diagnose concurrent faults, it is possible to use several different techniques. The layered clustering technique includes three different layers which utilise different diagnosing techniques. The first one distinguishes two of the faults with the highest RPNs, which are abrasion of the valve plate and insufficient inlet pressure. The second diagnosis layer recognizes roller bearing fault with an RPN of 96. The third layer determines slipper and swash plate eccentricity and clearance increase between piston and slipper. The RPNs of these are 72. [11]

In the first layer abrasion of the valve plate can be diagnosed based on the increase in overall leakage, which can be determined when the leakage rises over the defined threshold. The second fault in the first layer, insufficient inlet pressure, can be detected from the discharge pressure signal, which is converted from a time domain to a frequency domain using Fast Fourier Transform (FFT). [11] This fault will cause peaks in amplitude, seen in Figure 11, which indicates an insufficient inlet pressure fault.

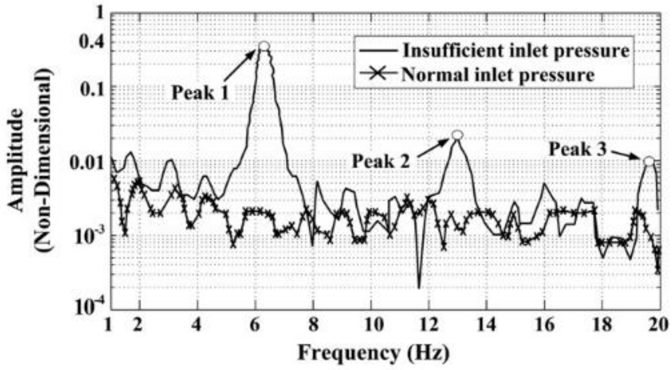


Figure 11 *Spectrum analysis* [11]

In the second layer, the wear of the roller bearing is diagnosed using an abnormal radial vibration signal. To diagnose this fault Du et al. [11] applied the cepstrum envelope algorithm to diagnose the fault adequately. This fault will also cause a peak in amplitude, as seen in Figure 12.

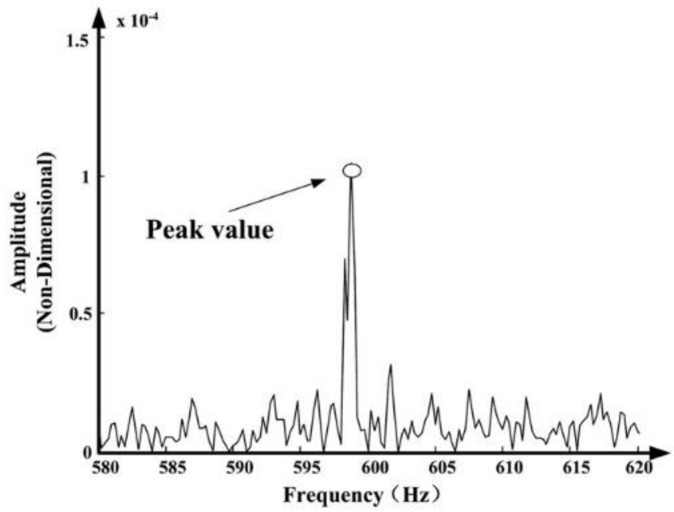


Figure 12 *The cepstrum envelope curve* [11]

In the third layer, clustering diagnosis based on the statistical Average Relative Power Difference (ARPD), which Du et al. [11] proposed, is used to diagnose the last failures. They proposed this clustering diagnosis algorithm ARPD instead of the classical FFT because the features of the last two failures are very weak and similar to each other. These failures are increasing clearance between piston and slipper and swash plate eccentricity, and these can be detected by utilising axial and radial vibration measurements.

After the experiments, Du et al. [11] concluded that the layered clustering algorithm can successfully detect the five main faults occurring simultaneously. Their proposed algorithm, which was used in the last layer, is more reliable and more accurate than the technique they compared it to, which is based on classical FFT.

4.3 Summary

Often analysis is based on the knowledge of fault and the conducted analysis can be utilized in establishing new diagnosing techniques.

Most of the diagnosing techniques are signal-based, and due to that, the data collected from sensors is utilised. Sensors that are chosen for the system and the amount of those vary depending on the fault and diagnosing technique. The most commonly used sensors are vibration, pressure, flow, and noise sensors.

Furthermore, the diagnosing techniques vary but the goal is often the same – to find a reliable technique to predict and/or diagnose faults accurately. Even though most of the current diagnosing techniques focus on diagnosing one fault, ways to successfully diagnose concurrent failures would more beneficial in real-life applications.

5. CONCLUSIONS

As the hydraulic pump is one of the main components in many kinds of mobile machines, the possible failure is crucial for the machine's operation. The main focus of this work is on the failure of positive displacement pumps, which are commonly used in off-road machines.

Failure modes of hydraulic pumps can be generated by several different causes. These causes can be divided into four main groups, operation and maintenance, installation, design, and manufacture. The main group out of these is operation and maintenance, which includes causes such as contamination, improper fluid and viscosity, pressure shocks, and low fluid level in the tank. In the hydraulic system, contamination can be the cause of 70–80 % of failures. Because of this reducing occurring failures would require changes in the operation and maintenance of the machines and pumps.

Failure modes include several different faults, with various causes, and effects. These failures can be presented differently depending on the type of the pump, but even though the differences in structures and working mechanisms of pumps, the failure modes can have similarities in certain cases. For the three pump types, axial piston, external gear, and vane pumps, the most common fault is wear, which is usually caused by contamination or improper fluid. The effects of the failures are often unusual vibration and noise, but also changes in output pressure and flow are commonly presented with failures.

Analysing the faults depends on the reasoning and because of that several techniques have been established but often the analysis is based on the knowledge of fault. Usually, the goal of the analysis is to identify the fault and its causes and effects. This way it can be utilised in establishing a diagnosing technique.

So far multiple different diagnosing techniques have been established and most of those are signal-based, and therefore utilise the data collected from sensors. The sensors chosen for the system and the amount of those vary depending on the faults and diagnosing technique. The most used sensors are vibration, pressure, flow, and noise sensors. Some factors, including external load and non-linear dynamics of pumps, make diagnosis more difficult.

Even though the diagnosing techniques vary, the goal is often the same – to find a reliable technique to predict and/or diagnose faults successfully. Because most of the current diagnosing techniques focus on diagnosing one fault, ways to successfully diagnose concurrent failures would be needed. Due to this new research on diagnosing concurrent failures successfully and reliably would be beneficial.

REFERENCES

[1] S. Ruhi and M. R. Karim, "Selecting statistical model and optimum maintenance policy: a case study of hydraulic pump," *Springerplus*, vol. 5, no. 1, 2016, pp. 1–14, doi: 10.1186/s40064-016-2619-1.

[2] J. Harlan, "When a Pump Fails, the Whole System Fails: Hydraulic Pump Reliability," 2017, (accessed Jan. 07, 2021), https://www.hyprofiltration.com/blog/hydraulic-pump-reliability.

[3] B. Casey, "How to Determine Hydraulic Pump Condition Using Volumetric Efficiency," 2017, (accessed Feb. 13, 2021), https://fluidpowerjournal.com/how-to-determine-hydraulic-pump-condition-using-volumetric-efficiency/.

[4] H. Tang, Z. Fu, and Y. Huang, "A fault diagnosis method for loose slipper failure of piston pump in construction machinery under changing load," *Appl. Acoust.*, vol. 172, 2020, doi: 10.1016/j.apacoust.2020.107634.

[5] G. E. Totten and V. J. De Negri, "*SECOND EDITION HANDBOOK OF HYDRAULIC FLUID*," 2012, p. 944.

[6] X. Wang, S. Lin, S. Wang,Z. He, and C. Zhang, "Remaining useful life prediction model based on contaminant sensitivity for aviation hydraulic piston pump," *AUS 2016 - 2016 IEEE/CSAA Int. Conf. Aircr. Util. Syst.*, 2016, pp. 266–272, doi: 10.1109/AUS.2016.7748057.

[7] Denison Vane Technology, "Hydraulic Pumps & Motors Vane Troubleshooting Guide," 2012, p. 62.

[8] J. P. P. Gomes, B. P. Leão, W. O. L. Vianna, R. K. H. Galvão, and T. Yoneyama, "Failure prognostics of a hydraulic pump using Kalman Filter," *Proc. Annu. Conf. Progn. Heal. Manag. Soc. 2012, PHM 2012*, 2012, pp. 464–468.

[9] G. Xu, Z. Gao, X. Hu, and Y. Luo, "Modeling and Simulation of Aero-hydraulic Pump Wear Failure," 2017, pp. 8–14.

[10] J. Ma, J. Chen, J. Li, Q. Li, and C. Ren, "Wear analysis of swash plate/slipper pair of axis piston hydraulic pump," *Tribol. Int.*, vol. 90, 2015, pp. 467–472, doi: 10.1016/j.triboint.2015.05.010.

[11] J. Du, S. Wang, and H. Zhang, "Layered clustering multi-fault diagnosis for hydraulic piston pump," *Mech. Syst. Signal Process.*, vol. 36, no. 2, 2013, pp. 487–504, doi: 10.1016/j.ymssp.2012.10.020.

[12] J. Fabiś-Domagała, "Analysis of defects and failures of hydraulic gear pumps with the use of selected qualitative methods," *Tribologia*, 2017, pp. 33–38.

[13] J. A. McLinn, "Life testing hydraulic gear motors," *Proc. - Annu. Reliab. Maintainab. Symp.*, 2005, pp. 245–249, doi: 10.1109/rams.2005.1408369.

[14] J. Fabiś-Domagała, G. Filo, H. Momeni, and M. Domagała, "Instruments of identification of hydraulic components potential failures," *MATEC Web Conf.*, vol.

183, 2018, doi: 10.1051/matecconf/201818303008.

[15] H. Shen, Z. Li, L. Qi, and L. Qiao, "A method for gear fatigue life prediction considering the internal flow field of the gear pump," *Mech. Syst. Signal Process.*, vol. 99, no. June 2016, 2018, pp. 921–929, doi: 10.1016/j.ymssp.2016.09.022.

[16] E. Lisowski and J. Fabiś, "Prediction of potential failures in hydraulic gear pumps," *Issn*, vol. 10, no. 3, 2010, pp. 1897–3310.

[17] John Watton, "*Modelling, Monitoring and Diagnostic Techniques for Fluid Power Systems,* " 2007, p. 360.

[18] J. Lee, F. Wu, W. Zhao, M. Ghaffari, L. Liao, and D. Siegel, "Prognostics and health management design for rotary machinery systems - Reviews, methodology and applications," *Mech. Syst. Signal Process.*, vol. 42, no. 1–2, 2014, pp. 314–334, doi: 10.1016/j.ymssp.2013.06.004.

[19] G. L. Zuo, F. L. Niu, Y. Cheng, and Y. X. Zhang, "Study on the fault diagnosis of gear pump based on RBF neural network," *Appl. Mech. Mater.*, vol. 556–562, 2014, pp. 2957–2961, doi: 10.4028/www.scientific.net/AMM.556-562.2957.

[20] J. Dai, J. Tang, S. Huang, and Y. Wang, "Signal - Based Intelligent Hydraulic Fault Diagnosis Methods : Review and Prospects," *Chinese J. Mech. Eng.*, 2019, doi: 10.1186/s10033-019-0388-9.

[21] S. Amin, C. Byington, and M. Watson, "Fuzzy Interference and Fusion for Health State Diagnosis of Hydraulic Pumps and Motors," *Annu. Meet. North Am. Fuzzy Inf. Process. Soc.*, 2005.

[22] Y. Jia, M. Xu, and R. Wang, "Symbolic important point perceptually and hidden markov model based hydraulic pump fault diagnosis method," *Sensors (Switzerland)*, vol. 18, no. 12, 2018, doi: 10.3390/s18124460.

[23] Y. Tian, C. Lu, and Z. L. Wang, "Approach for Hydraulic Pump Fault Diagnosis Based on WPT-SVD and SVM," *Appl. Mech. Mater.*, vol. 764–765, 2015, pp. 191–197, doi: 10.4028/www.scientific.net/amm.764-765.191.

[24] H. Yu, H. Li, Y. Li, and Y. Li, "A novel improved full vector spectrum algorithm and its application in multi-sensor data fusion for hydraulic pumps," *Meas. J. Int. Meas. Confed.*, vol. 133, 2019, pp. 145–161, doi: 10.1016/j.measurement.2018.10.011.

[25] Y. Gao, Q. Zhang, and X. Kong, "Wavelet-based Pressure Analysis for Hydraulic Pump Health Diagnosis," *Trans. Am. Soc. Agric. Eng.*, vol. 46, no. 4, 2014, pp. 969–976, doi: 10.13031/2013.13952.

[26] S. Liu, L. Ding, and W. Jiang, "Study on application of Principal Component Analysis to fault detection in hydraulic pump," *Proc. 2011 Int. Conf. Fluid Power Mechatronics, FPM 2011*, no. 4, 2011, pp. 173–178, doi: 10.1109/FPM.2011.6045752.

APPENDIX A: TERMINOLOGY

This appendix explains the terms which are used in this work.

Foaming and aeration

Gas, usually air, getting mixed in the fluid is called aeration. Air can be in the system as “free air”, meaning it’s not completely in contact with the fluid. Entrained air is suspended in the fluid, often as small bubbles, and dissolved air is fully mixed into the fluid. This can be caused by improper reservoir design. Foaming is presented when trapped air builds on the surface. Aeration is one cause of foaming in a hydraulic system. Other causes of foaming may be fluid contamination or improper reservoir. [5, pp. 120, 124–127]

Cavitation

The phenomenon where high-pressure drop causes the pressure to be less than the gas’ saturation pressure or the liquid’s vapor pressure. This will cause small cavities that are filled with vapor. When pressure rises higher these cavities will collapse causing a strong shock wave. [5, pp. 151]

Over pressurization

In the case of over pressurization, the pressures used in the system, are too high for the components to handle. One reason for over pressurization can be a failure of another component, for example, the failure of a relief-valve. [5, pp. 481]

Improper viscosity

Viscosity describes the fluid's internal friction or its resistance to flow. If the viscosity is too high, the pump may cavitate, the pressure drop may increase, the temperature of the fluid may rise, or the mechanical efficiency may decrease. [5, pp. 182, 481–482]

Fluid oxidation

Oxidation is a chemical mixture of hydraulic fluid and oxygen. Fluid oxidation causes chemical reactions that will lead to corrosion. By-products of oxidation can block the suction strainer and cause cavitation and decrease flow rate. [5, pp. 479]

Contamination

Hydraulic fluid can be contaminated when a foreign material gets into the system. Different contaminants can be solid particles, other fluids, or gases. Contamination can be reduced with proper filtering and maintenance. [5, pp. 478]

Abrasive wear

Removal of surface material, while harder material is moving along softer material, is called abrasive wear. Wear can be caused by hard particles in the contaminated fluid. The size, shape, hardness, and toughness of the particles will affect the wear process. [5, pp. 485]

Adhesive wear

Surface asperities in sliding contact under a load can cause adhesive wear. If generated heat is high enough, shearing and material transfer will occur. If larger surfaces are in contact, a seizure may occur. Wear debris caused by seizure may lead to abrasion wear. Good lubrication will decrease the possibility of abrasive and adhesive wear [5, pp. 485, 487].