Failure Monitoring and Predictive Maintenance of Hydraulic Cylinder—State-of-the-Art Review

Vignesh V. Shanbhag, Thomas J. J. Meyer, Leo W. Caspers, and Rune Schlanbusch

***Abstract*—A hydraulic cylinder is a mechanical actuator that is widely used in different industries such as construction, manufacturing, aerospace, and offshore oil and gas. Seal wear in hydraulic cylinders results in hydraulic fluid leakage or contamination of the hydraulic fluid. Untimely, failure of a hydraulic cylinder increases the maintenance cost and reduces productivity. Therefore, condition monitoring of the hydraulic cylinder is necessary to understand the current state of equipment. In the literature, there have been numerous documented attempts to perform condition monitoring of hydraulic cylinders using different methods, based on fluid properties, pressure, vibration, and acoustic emission. However, there have been limited attempts to present a state-of-the-art review of condition monitoring of hydraulic cylinders. This article presents an overview of the methods used for the condition monitoring of hydraulic cylinders, including the detection of different failure modes using different sensors, the separability of fault conditions using sensor-based features, and the ability to pick up incipient faults by sensor-based features. This information is required for new readers in this area of expertise. This article summarizes different condition monitoring methods that have been used from its early implementation to very recent dates, aiming at clarifying recent advances and identifying challenges in the research of the condition monitoring of hydraulic cylinders. It is anticipated that the information presented in this article will be beneficial for new researchers and provide directions for future research in the area of condition monitoring of hydraulic cylinders.**

***Index Terms*—Condition monitoring, failure mode, fluid contamination, fluid leakage, hydraulic cylinders.**

I. Introduction

A HYDRAULIC cylinder is a linear actuator that uses a pressurized fluid to produce linear force and motion. It exhibits both efficient power to weight ratio and power to size ratio [1], [2]. It also exhibits a rapid response, smooth reversal, inherent safety for external overloading and precise positioning of the heavy load [3], [4]. Due to these advantages, hydraulic cylinders are used in different applications such as aerial platforms, excavators, forklifts, drilling, hydraulic jacks, compensating systems, wireline tensioning systems, and hydraulic fracturing. The hydraulic cylinder global market is expected to grow from the current 14.9 billion U.S. dollar to 19.4 billion U.S. dollar by 2024 at the compound annual growth rate of 5.4%. Hydraulic cylinders used in material handling applications are expected to cover a share of 60% in the forecast period [5]. The continuous use of these hydraulic cylinders is limited by the deterioration of the seal systems. A rod seal system in a hydraulic cylinder typically consists of a wiper, a secondary and primary rod seal, and rod bearing elements. A piston seal system includes a piston seal and piston bearing elements [6], [7]. If a seal is not replaced in time it will lead to fluid leakage or contamination of the fluid with particles or process fluids from the environment. As the piston rod extends, fluid leaks past the seal in the form of a thick fluid film. As the piston rod retracts, the contaminants stick to this fluid film on the piston rod and are drawn into the system together with the fluid film. Contaminants such as dust, water, dirt, and chemicals thus enter the fluid in the hydraulic cylinder. These contaminants increase the rate of wear mechanisms such as abrasive wear, scoring of moving parts, adhesive wear, fatigue wear, and corrosion of hydraulic cylinder parts [8], [9]. Hard contaminants, such as steel, can cause severe damage by scratching the hydraulic cylinder seals or by scoring metal surfaces. Soft contaminants such as cloth fibers can cause clogging of the hydraulic control elements such as an orifice. Water contaminants in the fluid can cause corrosion of components and can deteriorate hydraulic fluid properties [10]. Therefore, fluid contamination is an important cause of hydraulic cylinder failures mainly because it leads to scores on the piston rod, seal wear, and leakage [11]. According to the works of literature [10], [12], [13], 65%–90% of hydraulic system failures are caused by fluid contamination. Therefore, to reduce the effect of fluid contamination on performance of hydraulic cylinder, it is important to monitor the fluid cleanliness level at regular intervals.

Internal fluid leakage of hydraulic cylinders can cause reduction of force exerted by the cylinders and instability of the piston rod movement. Heavy internal fluid leakage can also cause reduction in linear velocity. Consequences of external seal failure include increased chance of injury due to fluid spilling, risk of health problems, fire hazard risk, and risk of

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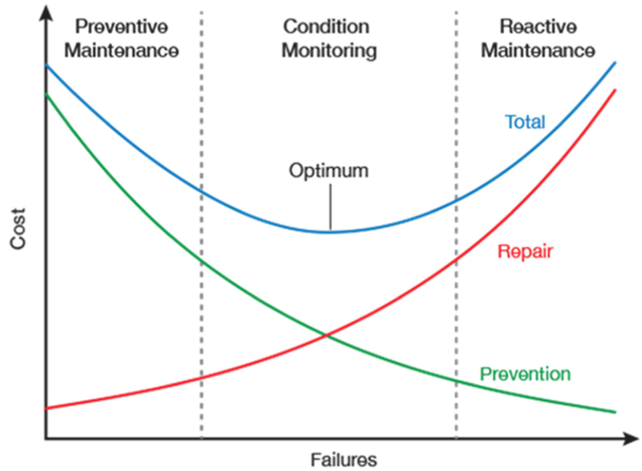

Fig. 1. Cost associated with conventional and condition-based maintenance strategies [20], [21] (reproduced from [21] as per Creative Commons CC BY 3.0 license).

environmental contamination. The economic consequences due to leakage from hydraulic cylinders are huge. For example, a hydraulic leak of one drop per second is equal to 420 million gallons of oil over 12-month period. Alone in North America, 100 million gallons of oil could be saved every year if external fluid leakage from hydraulic systems was eliminated [9]. Oil leakage in offshore oil and gas (O&G) industry also affects human life. A 2019 study done in Nigeria, which is the largest oil producer country in Africa, discovered that the nearby oil spills increased the neonatal mortality rate by 38.3 deaths per 1000 live births [14]. Considering the effect of oil leakage on economy and human life, if not total elimination of oil leakage, it is important to atleast minimize oil leakage. As hydraulic seals are concealed within the hydraulic cylinder it is difficult to assess the seal condition through visual inspection without atleast partly disassembling the system. Unpredictable failure of a hydraulic seal causing failure of the hydraulic cylinder leads to increased maintenance costs, possibly collateral damage to other parts of the cylinder and reduction of its availability that can be the most significant cost driver [15].

Conventional maintenance strategies adopted in industries are of two types: 1) reactive maintenance strategy; and 2) preventive maintenance strategy. In reactive maintenance strategy, the machine is repaired after a major breakdown. The preventive maintenance strategy follows a schedule for inspection and replacement of wear parts before failure, which results in machine downtime even if the equipment did not actually require maintenance [16]. The reactive and preventive maintenance strategies do not consider the current health of the equipment, resulting in higher cost and maintenance time. The alternative to the conventional maintenance strategies is condition-based maintenance, which considers the information of current health of equipment before deciding to perform maintenance of equipment [17]. By adopting condition-based maintenance, maintenance of equipment is only performed when it is effectively required [16], [18], [19]. Fig. 1 represents the relation between maintenance cost and failures for different maintenance strategies. The initial investment that is required to implement condition monitoring can be high, however, they can be recovered over the years by saving on total maintenance cost (see Table I).

TABLE I
COST SAVING BY IMPLEMENTING ONLINE CONDITION MONITORING FOR GEARBOX [25]

	Gearbox failure cost (USD)	Cost if online condition monitoring is used (USD)	Cost savings (USD)
Repair and replacement costs	250 000 (New gearbox and work costs)	30 000 (Gearbox bearings, main shaft and work costs)	220 000
Revenue loss caused subsequent downtime	26 000	2 000	24 000
Other costs	150 000 (Crane)	75 000 (Crane)	75 000
Total	426 000	107 000	319 000

Apart from spare part cost and repair cost, maintenance cost also includes the cost due to downtime. This downtime consists of identification time, time for maintenance planning, time for service, time for accessibility, and time for maintenance [22]. In the process industry, cost of unplanned maintenance can be upto 250 000 USD per hour [23]. Allied reliability firm [24] performed a survey of 25 plants of five companies to understand the correlation between reliability, maintenance, costs, safety, and productivity. A correlation was observed between predictive maintenance applied and the maintenance cost. The maintenance cost substantially decreased with the increase of predictive maintenance. Barber and Golbeck [25] used a case example to explain the cost saved by implementing online condition monitoring. By implementing online condition monitoring for a gearbox, upto 319 000 USD could be saved (see Table I). Unplanned maintenance time can be eliminated by using real-time accurate condition data as this would allow the operator to make scheduled maintenance based on the health of equipment [26], [27]. In the O&G industry, the operating costs include day to day operations of the facilities and maintenance of the platforms and wells. By end of 2019, 87 fields in the Norwegian continental shelf were producing O&G. The total operating costs for the year was approximately 6 billion U.S. dollar. The O&G companies are engaged in reducing these operating costs [27], [28]. Therefore, even a minor reduction in maintenance cost will provide a big relief to the O&G operating companies. As hydraulic cylinders are widely used in O&G industry, condition-based maintenance strategies for the hydraulic cylinders are required to avoid unscheduled maintenance and cost associated with untimely failure of equipment.

Monitoring the health of components in a hydraulic cylinder can be performed based on direct or indirect methods. In direct monitoring methods, the changes of components or machine tools are measured on the components themselves, e.g., through visual inspection or geometric measurements. Despite many attempts, direct monitoring methods such as machine vision, surface characterization, and visual inspection have not yet proven to be economically viable [29]. Also, direct monitoring methods

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are difficult to implement for hydraulic cylinders as the seals are concealed within the system. Removal of seals to measure geometric changes is time-consuming and reduces the availability of the cylinder. A conventional method of measuring fluid leakage is done by sensing the fluid level in a measuring container that collects the fluid from the leakage port or by weighing the fluid that is collected in this container [15]. However, by the time the fluid leakage has started, it is already too late for a predictive maintenance strategy. In indirect monitoring methods, features of the signals from sensors are correlated with the changes of the condition of the component. These indirect monitoring methods can be used for real-time monitoring of practical applications [30]. Therefore, this article will focus only on literature papers that have used indirect monitoring methods to study the health of the hydraulic cylinders. There have been very little attempts to present a state-of-the-art review of methods and sensors that can be used to monitor defects in hydraulic cylinders. Therefore, in this article, a state-of-the-art review of sensors and methods that have been used to monitor fluid contamination and fluid leakage in hydraulic cylinders is presented. The fluid contamination and fluid leakage are used as indicators for failure monitoring and predictive maintenance of hydraulic cylinders for the following two reasons: 1) contaminants in fluid affects the surface quality of the piston rod and the seal surface, resulting in premature failure of the components; and 2) seal wear causes either internal or external fluid leakage thereby affecting energy efficiency of the hydraulic cylinder, loss of fluid, safety issues, or higher maintenance cost [7], [9].

It is important to first understand the different failure modes and related wear mechanisms that are observed in hydraulic cylinders. The rest of this article is organized as follows. In Section II, different defects that are observed in hydraulic cylinder are discussed. In Section III, the literature related to fluid-based condition monitoring of hydraulic cylinders will be discussed, followed by a discussion on sensors used to diagnose leakage in hydraulic cylinders in Section IV. In Section V, a summary of different condition monitoring methods used for hydraulic cylinders is presented, and the knowledge gap in the literature is discussed. Finally, Section VI concludes this article.

II. Defects Observed in Hydraulic Cylinders

The hydraulic cylinder working efficiency is affected by a variety of reasons such as fluid contamination, fluid leakage due to seal defect, worn piston rods or rod bearings, internal corrosion or a broken eye bearing [31]. As seal wear can lead to fluid contamination and fluid leakage [10], [11], [31], these two topics are discussed in this article.

A. Fluid Contamination

Pressurized fluid is the medium through which power is transferred in a hydraulic cylinder. Therefore, the condition of the fluid in a hydraulic cylinder is an important source for early detection of critical faults. For example, excessive metallic particle contamination in the fluid often indicates wear of components and can result in overheating, component failure, or even system malfunction. Nonmetallic particles often indicate that the fluid circulation is not well sealed against foreign particles from the outside environment [32]. A secondary function of the fluid is to reduce friction and wear by providing a continuous film layer between surfaces in relative motion. Other secondary functions of the fluid are to protect the components against corrosion, maintain correct temperature of the working parts and flush away contaminants [33]. Variations in physical, chemical, electrical, and optical properties change the characteristics of the fluid. To monitor the health of the fluid in a hydraulic cylinder, the following physical or chemical values need to be considered. Some of the basic fluid degradation features are as follows.

1) Water Contamination: Depending on the temperature, age, and type of fluid, nonwater-based hydraulic fluids can withstand as much as 200–600 ppm of water in the dissolved state. Aged hydraulic fluids can hold three to four times more water in the dissolved state when compared to new fluid. Once the amount of water in fluid reaches its maximum level in dissolved state, it reaches the saturation level. Beyond the saturation level, the excess water can be present as either a separate water phase or as an emulsion. Physical fluid properties that are affected by the presence of water are viscosity, lubricity, load-carrying characteristics, and power transfer characteristics (compressibility). Chemical properties of fluid that are affected due to the presence of water are the total acid number, thermo-oxidative stability, deposition characteristics, and premature additive depletion [34]–[36].

2) Particle Contamination: The presence of particle contaminants in hydraulic fluids is regarded as one of the major sources of failure in hydraulic systems [37], [38]. Particle contaminants reduce the ability of control valves to control fluid flow and pressure, thus wasting energy and generating excess heat [38]. Particle contaminants in hydraulic fluid also accelerate the wear of components in the system [39]. According to Casey [39], the rate at which the component damage occurs due to particle contaminants depends on a number of factors such as internal clearance of the components within the system, size of particles, and quantity of particles. If the size of particle contaminants is larger than the internal clearance of the components within the system, they do not result in severe degradation. If the size of the particle contaminants is nearly equal to the size of the component clearances, they may cause damage due to friction generated between parts in relative motion. The most dangerous particle contaminants are the ones whose particle size is smaller than the internal clearance of the components. Therefore, particle sizes that are less than the size of the internal clearance of the hydraulic cylinder can be highly abrasive and can cause major damage to the hydraulic cylinder if the particles are present in sufficient quantities. The source of particle contamination in hydraulic fluids can be categorized into four categories: contaminated new oil, built-in contamination, ingressed contamination, and internally generated contamination [12], [40], [41]. Due to particle contamination in hydraulic fluids, the hydraulic components can undergo different types of wear mechanisms such as abrasive wear, adhesive wear, fatigue wear, erosive wear, cavitation wear, aeration wear, and corrosive wear [12], [40]–[43]. Abrasive wear and surface fatigue account for 90% of the component failures in hydraulic systems [40]. Based on the severity of the failure due to

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contaminants in hydraulic fluid, the failure can be categorized into three categories: degradation failure, intermittent failure, and catastrophic failure [12], [40], [44].

3) Air Contamination: Oxidation is defined as a chemical reaction that occurs in the combination of hydraulic fluid and oxygen. Oxidation in hydraulic fluids is accelerated by a number of factors such as: high temperatures, presence of water, acidity, and catalysts such as copper. Over time, the rate of oxidation increases. Generally, above 60 °C, for every 10 °C rise in temperature, oxidation will reduce the life of hydraulic fluids by half. With an increase in oxidation level in hydraulic fluids, the viscosity of fluid increases and also the total acid number increases, which can result in sludge deposits [44], [45].

B. Fluid Leakage

In industry, fluid leakage is used as a key indicator to monitor the energy efficiency of hydraulic cylinders. Leakage from hydraulic cylinders is considered a concern. It can be classified into two types: external leakage and internal leakage [46]. External leakage may be due to degradation of the dynamic seal system between the rod and the cylinder head, failure of the hydraulic supply line or in the connection between the valve and the actuator chambers. Internal leakage is due to degradation or wear in the piston seal system located between the movable piston and the cylinder shell [47]. Fluid leakage in hydraulic cylinders occurs due to numbers of factors such as follows:

1) *Seal Defect:* Leakage caused by seal defects accounts for 65.9% of all leakages [48]. Seal defects occur due to a number of reasons such as aging of seal material, change in dimensional tolerance due to variation in temperature, humidity, fluid contamination or excessive load and pressure. Some of the common types of seal defects are as follows [49].
   a) *Seal Deterioration*: Seal loses its elasticity and crumbles easily [Fig. 2(a)]. It occurs due to a high fluid temperature.
   b) *Seal Extrusion*: Dynamic or static side of seal shows signs of extrusion [Fig. 2(b) and (c)]. It occurs due to an excessive system pressure.
   c) *Grooving*: Dynamic lip shows signs of axial cuts and grooves [Fig. 2(d)]. It occurs due to the presence of particle contaminants in the fluid.
   d) *Fracturing*: Seal undergoes loss of material, cracks, or broken surface [Fig. 2(e)–(h)]. It occurs due to excessive system pressure or due to fluid breakdown.
   e) *Hardening*: Dynamic side of the seal or sometimes entire seals is hardened and shows signs of cracks and loss of elasticity [Fig. 2(i) and (j)]. It occurs due to high stroke speed, fluid temperature, or incompatible fluid for the seal.
   f) *Scarring*: Lip of the seal is cut, or dynamic side of the seal shows excessive scratches [Fig. 2(k) and (l)]. It occurs due to mishandling of the seal during installation or in store. It may occur also due to rod damage or fluid contamination.

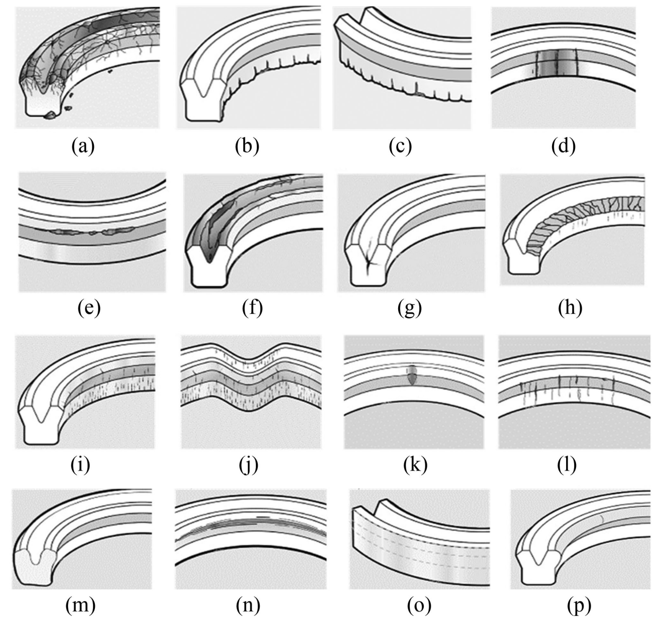

Fig. 2. Different types of seal defect. (a) Deterioration; extrusion on (b) dynamic side (c) static side; (d) grooving; fracturing on (e) dynamic side (f) pressurized surface (g) V portion (h) dynamic side; hardening on (i) dynamic side (j) entire seal; scarring on (k) lip (l) dynamic side, (m) swelling; wear on (n) dynamic lip (o) dynamic face (p) dynamic lip [49] (reproduced from [49] with permission from Machine Design).

   g) *Swelling*: Seal material has become softened and deformed [Fig. 2(m)]. It occurs due to incompatible fluid for the seal.
   h) *Wear*: Dynamic side of the seal shows excessive wear, dynamic face of the seal becomes glossy or dynamic face of the seal is worn to a rounded egg shape [Fig. 2(n)–(p)]. It occurs due to excessive lateral load, improper lubrication or if rod and cylinder bore are not concentric.
2) *Quality of Product Assembly:* Due to nonstandardized methods and tools used during product assembly, it results in scratches on seals. Fluid leakage due to this defect accounts for 17% in total [48].
3) *Casting or Machining Defects:* Fluid leakage caused due to casting porosity accounts for 8% in total. Fluid leakage caused due to improper tolerance of seal grooves accounts for 3.4% in total [48].
4) *Design Defects:* Fluid leakage caused due to unreasonable design of parts or sealing surface accounts for 2.3% in total [48].
5) *Surface Treatment Defects:* Fluid leakage caused due to the peeling of coating on rod surface accounts for 1% in total [48].

III. Condition Monitoring of Fluids in Hydraulic Cylinders

Different degradation features that affect fluid quality in hydraulic cylinders are high temperature, air, water, chemical contaminants, wear debris, or dust [50]. Once fluid contamination is

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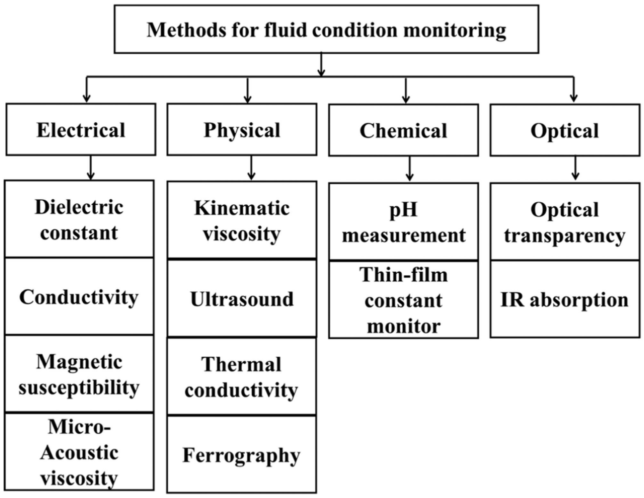

Fig. 3. Principles for different fluid condition monitoring methods [32].

discovered, appropriate measures can be taken by using a fluid treatment system such as VacuClean from Bosch Rexroth [51]. However, the degradation features related to fluid contamination can be monitored using different principles of oil condition monitoring methods based on electrical (magnetic), physical, chemical, and optical principles at very initial stages (see Fig. 3). Physical and chemical methods are direct monitoring methods of fluid condition monitoring, whereas electrical (magnetic) and optical methods are indirect methods. The indirect methods monitor a specific property of the fluid and correlate the acquired data to the fluid condition [32], [52]. As this article mainly focusses on indirect condition monitoring methods, only the electrical (magnetic) and optical methods are discussed here.

A. Electrical (Magnetic) Methods

In electrical (magnetic) methods, the degradation of fluid is measured by monitoring electrical and magnetic properties of the fluid [53]. Some of the electrical or magnetic features that have been used to monitor fluid degradation are dielectric constant, conductivity, magnetic susceptibility, and microacoustic viscosity.

1) Dielectric Constant: In fluid condition monitoring, a change in the dielectric constant indicates the presence of water, air, particles, a change in the chemistry, or a change in temperature and density [54]. A capacitor sensor has widely been used to measure a change in the dielectric constant. For example, Raadnui and Kleesuwan [50] and Dingxin *et al.* [55] designed and developed a capacitor sensor to detect minor variation in the sensors capacitance. In the experimental tests, changes in the dielectric constant had a good correlation with the chemical and physical properties such as aged behavior and the presence of water and ferrous powder. Liu *et al.* [56] measured the lubricant quality for a marine diesel engine by having a combination of a capacitor sensor and a ferro particle detector. Because of this combined approach, it was possible to identify nonferro particles and ferro particles. Guan *et al.* [57] used dielectric spectroscopy, also known as electrochemical impedance spectroscopy, to measure degradation of engine oil. Dielectric spectroscopy is an analytical technique based on the interaction between dielectric material and electromagnetic energy in the radiofrequency and microwave range. Using dielectric spectroscopy with statistical methods such as partial least square, it was possible to measure oxidation content, total acid number, and insoluble content of the oil. Similarly, Ulrich *et al.* [58] used dielectric spectroscopy with multivariate data analysis to simultaneously predict soot concentration and diesel in engine oil. Soot and diesel contaminants in engine oil affect the impedance frequency range. For example, soot influences the impedance over the entire frequency range and diesel influences the impedance only at low-frequency range.

To measure the fluid condition in hydraulic cylinders there are numerous sensors based on dielectric sensing available from different industries. For example, the fluid condition sensor from Parker Kittiwake [59] detects the change in water and acid levels based on the principle of dielectric sensing. Similarly, a fluid condition sensor from HYDAC [60] measures the aging and mixing of fluids by monitoring relative changes in the dielectric constant, fluid viscosity, temperature, and moisture content. A combined oil condition and moisture sensor from CMT monitoring systems [61] uses electro impedance spectroscopy technology to monitor water content in the fluid. Similarly, an oil quality and water contamination sensor from Poseidon systems [62] uses electro impedance spectroscopy to measure water content in the fluid. The advantages of fluid monitoring sensors based on the dielectric constant are degradation feature coverage, low complexity in data processing, and that they can be used continuously, enabling online monitoring [32].

2) Conductivity: In fluid condition monitoring, a change in conductivity indicates the presence of metallic debris, broken fluid molecules or increase of the total acidic number. The conductivity of fluids increases with an increase in ion concentration and mobility [63]. The conductivity measurement of hydraulic fluids also helps preventing the damage of hydraulic equipment from electrostatic discharges. The conductivity is measured for old as well as new fluids. The process of conductivity measurement is now performed in accordance with ASTM D2624 standards [64]. These measurement standards were originally developed for inspecting jet fuels to avoid accidents due to fuel charging [65]. Moon *et al.* [66] developed the multiwall carbon nanotubes sensor to monitor the conductivity change in the engine oil. The output of the carbon nanotube sensor was compared with the total acidic number of the oil. The behavior of the measured conductivity showed high covariance with the total acidic number. Basu *et al.* [67] measured the conductivity of two types of engine oils and compared its performance with changes in additives, antioxidants, total acidic number, and viscosity during various stages of oil degradation (Stages 1–4). In the first stage, with depletion of the additives, the conductivity of oils reduces. In the second stage, with depletion of antioxidants, the conductivity of oils was nearly steady. In the third stage, with an increase of the total acidic number, the conductivity of oil increases. In the fourth stage, with an increase of viscosity, the conductivity gradually decreased.

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Circulating fluid can build a static charge in the fluid due to molecular friction, which may result in electrical arching within the fluid body, charring the fluid in its path [68]. Therefore, for hydraulic systems, there are a number of instruments available in the market to measure the conductive properties of a fluid. For example, lubrication condition sensor from Argo Hytos [69] uses a combination of features such as specific conductivity, relative permittivity, fluid temperature, and relative humidity to determine aging, type, mixture, and remaining useful life (RUL) of the fluid. Similarly, the fluid condition monitoring sensor from Parker [70] measures features such as conductivity, permittivity, temperature, pressure, and moisture content to determine contamination ingress and fluid aging.

3) Magnetic Susceptibility: Metallic particle contaminants in hydraulic fluids results in surface fatigue, particle-induced abrasion, and motion impediment of sliding and rolling parts. Also, metallic particles are a root cause of base oil oxidation and aging of fluids [71]. Halderman and Mitchell [72] inspected the ferromagnetic particles in fluids using a magnetic plug. The magnetic plug was placed in the flow of oil and later removed for inspection of the ferromagnetic fragments. The ferromagnetic fragments were inspected using a microscope for condition monitoring analysis. Turner and Austin [53] used a magnetic susceptibility balance to monitor fluid degradation. It was expected that, with increase in fluid usage, the airborne contaminants would make the fluid increasingly paramagnetic. However, a poor correlation was observed between the magnetic susceptibility and oil usage. Tian *et al.* [73] developed a sensor based on the electromagnetic induction principle to monitor ferromagnetic debris in fluids. The sensor was sensitive to ferrous debris concentration up to 10 μg/mL. Du and Zhe [74] developed a sensor based on the inductive coulter counting principle to detect and distinguish ferrous and nonferrous particles. The sensor detected metallic debris in fluids by monitoring the change in inductance of a two-layer planar coil with meso-scale fluidic pipe crossing its center. The sensor was observed to be sensitive for metallic particles as low as 50 μm.

The total ferrous debris sensor from Parker Kittiwake [75] can be used to monitor ferrous debris in hydraulic fluids. Compared to conventional measuring devices such as magnetic plugs or a susceptibility balance, the total ferrous sensor can be used to measure in real time and provides the measurement value in parts per million (ppm). This sensor works on the principle of magnetometry and is sensitive for measuring ferrous particles as low as 1 μm. A wear debris sensor from Poseidon systems [76] can be used to monitor ferrous particles as well as nonferrous particles. This sensor has a sensitivity for ferrous particles of 40 μm and nonferrous particles of 150 μm and larger.

4) Microacoustic Viscosity: The viscosity feature is widely used to measure fluid degradation because of its independence of variation in most of the operating conditions. There are two types of viscometers: kinematic viscometers (physical) and microacoustic viscometers (electrical). By using a viscometer, it is possible to detect oxidation, water contamination, particle contaminants, and fluid dilution [32]. An acoustic viscometer is small in size when compared to a conventional mechanical and electromechanical viscometer. Because of its small size, it can be immersed in the fluid and can provide instantaneous fluid health data to the operator [77]. Jakoby *et al.* [78] developed a microacoustic viscosity sensor to measure viscosity and temperature. The sensor contained an integrated heater and temperature sensor such that temperature of the fluid sample was directly controlled at the sensitive surface. Compared to conventional viscosity measuring devices, this sensor required less heating power and shorter measurement time. Agoston *et al.* [79] used microacoustic sensors for condition monitoring of engine oil. The sensor signal was found to correlate well with fluid oxidation and total acidic number of the fluid.

In industry, there are companies that provide acoustic viscometers to monitor the viscosity for hydraulic fluids. For example, ViSmart from Vectron International [80] can be used for an instantaneous viscosity data stream. This sensor utilizes sound waves that are emitted along a surface of quartz crystal that is in contact with fluid. The loss of energy in the crystal is measured, which is directly proportional to the viscosity of the fluid. This sensor is unaffected by shock, vibration, or flow conditions. Therefore, it can be used in harsh environments.

B. Optical Methods

Sensors based on optical methods allow real-time measurements of fluids from new to fully aged fluids. Optical sensors are based on absorption spectroscopy, which correlates the data obtained with the degradation stage of the fluid. This correlation makes it possible to detect early signs of fluid degradation [81]. Optical methods based on optical transparency or reflectometry and IR absorption techniques are discussed in this article.

1) Optical Reflectometry or Transparency: Fluid degradation and fluid contamination can be detected by monitoring color change parameters. For example, Kumar *et al.* [82] developed an optical color sensor that converts color darkness into electrical resistance. Light is passed through one end of the fluid and its intensity is recorded at the other end of fluid. Transparency of fluid changes with degradation of the fluid, i.e., the degradation of fluids results in a change of the light absorbance intensity factor. Light absorbance intensity is then converted into electrical resistance. Ossia *et al.* [83] developed a color change detecting device based on the optical absorption principle to monitor degradation of synthetic hydraulic fluids. Color ratio was used as a feature to monitor fluid degradation. Color ratio is defined as the ratio of light intensity transmitted through the fluid in the red part of the visible electromagnetic spectrum to the light intensity transmitted through the fluid in the green part of the spectrum. This color ratio was observed to be sensitive to chemical degradation and less sensitive to particle contamination. Lopez *et al.* [84] developed a photonic sensor based on the principle of transmittance and diffuse reflectance photonic inspection of the fluid sample that is collected in a microcavity through a standard hydraulic fitting. The developed sensor can be directly immersed in the fluid and monitors fluid degradation, oxidation, acid number, and membrane patch colorimetry.

For hydraulic systems, there are several sensors based on optical methods that are commercially available to monitor fluid contamination. For example, contamination sensors from

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HYDAC lab [85] can be permanently mounted on the equipment to measure number of particles and size of particles in real-time. Similarly, oil particle monitoring from IFM electronics [86] and Bosch Rexroth [87] monitors particle concentration in fluids according to the light extinction principle and displays the fluid purity class on an liquid crystal display (LCD).

2) IR Absorption: When fluid degrades, a nitrate compound can be generated. The nitrate compound absorbs IR radiation of wavelength 6.13 μm. This principle can be used in sensors to monitor fluid degradation [32], [53]. Using IR absorption spectrum, it is possible to detect contaminants in fluid such as water and glycol [88]. Agoston *et al.* [89] used Fourier transform infrared spectroscopy (FTIR) to monitor degradation of engine oil. The oxidation index from the FTIR measurement was used for oil diagnosis. However, for online monitoring of fluids, the FTIR instrument is bulky and expensive. Therefore, Agoston *et al.* [89] developed an IR sensor that could be used for continuous monitoring of fluids. The developed sensor contained an IR detector and narrow-band IR filters. A good correlation was observed between oxidation value measured from the FTIR instrument and the IR sensor. Rauscher *et al.* [90] developed a sensor based on infrared spectroscopy to monitor fluid degradation in gearboxes. A multivariate partial least regression method was used to select an optical bandpass filter for monitoring oxidation, water and acid number. Bley *et al.* [91] developed a miniaturized multichannel IR spectrometer to monitor oxidation and water content in fluids. The developed IR sensor was used to test different fluids such as synthetic motor fluid, mineral hydraulic fluid, and ester-based hydraulic fluids. The IR sensor could detect increase in oxidation and water contamination for synthetic motor fluid and mineral hydraulic fluid. For ester-based hydraulic fluids, the IR sensor indicated the oxidation status. However, due to interference from water contamination, further signal processing was required.

To monitor fluids in hydraulic systems there are IR-based sensors available today. For example, the handheld IR sensor from CMT monitoring systems [92] can be used to monitor base oil degradation, additive depletion, and contamination. The sensor displays a number of fluid monitoring features such as water content, antioxidant depletion, glycol contamination, sulphate, oxidation, nitration, and phosphate. The inline fluid monitoring sensor from Zila [93] is based on multichannel infrared measuring cells. Based on the configuration, up to six parameters can be monitored at the same time such as oxidation, nitration, sulfation, water content, additive content, ethylene glycol, total acid number, and total base number.

IV. Condition Monitoring of Fluid Leakage in Hydraulic Cylinders

Currently, there are no visual features that can be used to monitor initial stages of fluid leakage in hydraulic cylinders until the fluid leakage is either visible or system performance is affected. Internal planned fluid leakage in hydraulic systems is performed by allowing the fluid to flow from the high pressurized zone to the low pressurized zone to lubricate, clean and cool specific components or areas, to avoid hotspots. A vulnerable fluid leakage point in hydraulic cylinders is where the piston rod emerges from the cylinder. Piston rod drift, seal damage, or the inability of the hydraulic cylinder to sustain external loads can result in major fluid leakage [94]–[96]. As the fluid leakage in hydraulic cylinders affects both the dynamic and static performance of the equipment, condition monitoring of hydraulic cylinders is required to maximize machine availability. To monitor leakage, there has been a growing motivation in recent years to depend less on model-based techniques and to focus more on signal-based techniques. For example, there are a number of attempts documented in the literature to perform fluid leakage monitoring using different sensors such as pressure, accelerometer, acoustic emission (AE), and torque (see Fig. 4). To analyze the sensor signal data, different signal processing techniques have been used such as: time-domain features, frequency-domain analysis, or time-frequency techniques (see Fig. 4). In this section, different sensors and signal processing techniques that have been used to monitor fluid leakage in hydraulic cylinders are discussed.

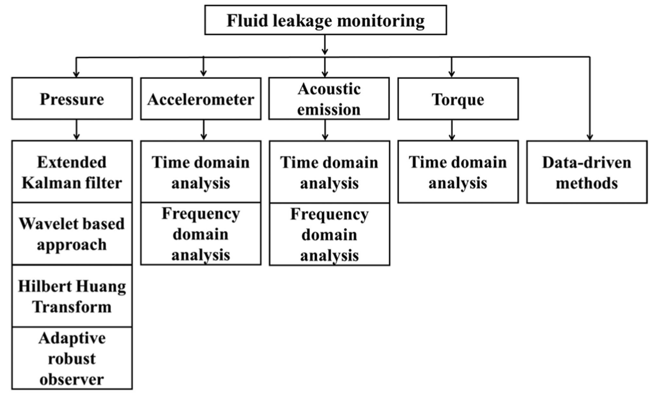

Fig. 4. Sensors and signal processing techniques used for fluid leakage monitoring.

A. Fluid Leakage Monitoring Using Pressure Sensors

Hydraulic pressure sensors are used to convert pressure measurements into analog electrical output signals. Fluid leakage in hydraulic cylinders affects the chamber pressure. Therefore, in different condition monitoring studies, pressure sensors are used to monitor fluid leakage. For example, An and Sepehri [97] used an extended Kalman filter (EKF) to monitor internal leakage at the piston seal and external leakage at the piston rod seal in hydraulic cylinders. An EKF-based estimator was constructed, which included nonlinear models of the hydraulic functions and the stick-slip friction and proposed the residual pressure error as a feature to monitor leakage faults. Under normal conditions, the EKF-based estimator correctly predicted the true states of system. In presence of the leakage faults, the level of residual pressure errors increased significantly between the measured and estimated inline pressure, indicating presence of faults (see Fig. 5). Using the residual error changes, it was possible to map internal and external leakages. During leakage, the level of the residual pressure error between measured and estimated

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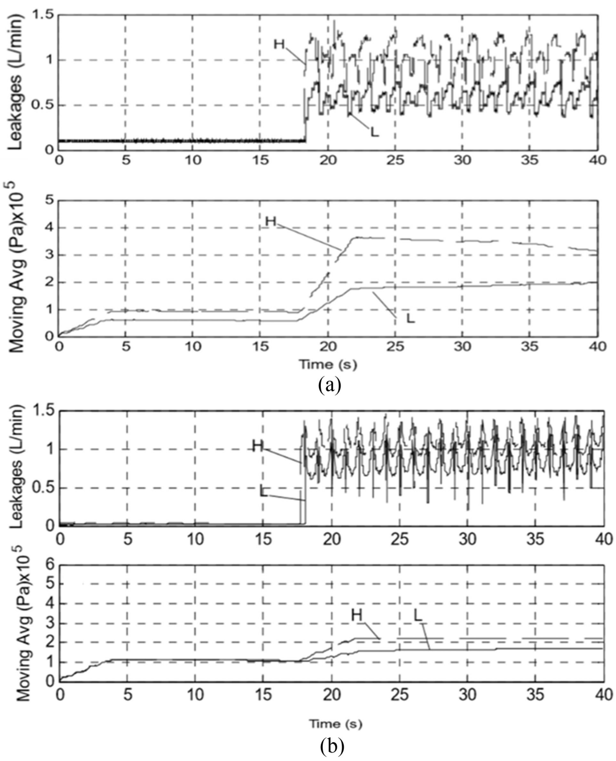

Fig. 5. Leakage and moving average residual pressure error responses for (a) external leakage and (b) internal leakage [97]. Note: Dashed line—High leakage, Solid line—Low leakage (reproduced from [97] with permission from Taylor & Francis online).

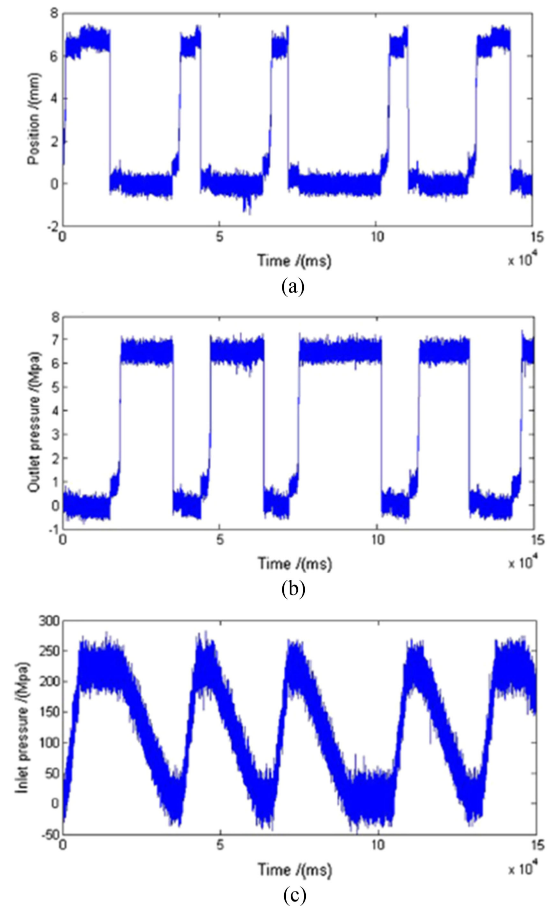

Fig. 6. Application of displacement and pressure sensors in hydraulic cylinders to study (a) position of piston, (b) outlet pressure, and (c) inlet pressure [103] (reproduced from [103] with permission from Elsevier).

pressure lines increased significantly with increasing leakage. Fluid leakage and rod displacement features were correlated with the residual pressure error.

There have been numerous attempts in the literature to monitor pressure signals from hydraulic cylinders experiencing fluid leakage using wavelet analysis. In wavelet analysis, the source signal is decomposed into the time and frequency domains simultaneously, thus allowing to focus on short time intervals for high-frequency components and longtime intervals for low-frequency components [98]–[100]. Goharrizi *et al.* [47], [101], [102] used the wavelet transform to monitor and quantify internal and external fluid leakage in hydraulic cylinders. A multi resolution decomposition technique was used to decompose the pressure signal into detail (high-frequency components) and approximate (low-frequency components) wavelet coefficients. The Daubechies 8 wavelet and magnitude of level two detail coefficient was observed to be sensitive to monitor internal leakage. A root mean square (RMS) feature extracted from the level two detail coefficient was used to identify normal and faulty conditions. In presence of fluid leakage, the RMS feature decreased in magnitude as well as energy. The developed methodology was capable of identifying the fluid leakage in the range of 0.2–0.25 L/min regardless of the type of feedback controller used, reference input, and loading condition. Similarly, to monitor external leakage, the RMS value of the level four coefficient was proposed to monitor external leakage. This RMS feature decreased with an increase in external leakage. The proposed methodology was observed to identify fluid leakage as low as 0.3 L/min. Zhao *et al.* [103] monitored different fluid leakage levels using wavelet packet analysis. Leakage levels were varied during the experiments by using orifices of different diameters varying from 0.25 to 0.3 mm. During the experiments, inlet and outlet pressure signals and the displacement signal of the hydraulic cylinder piston rod were collected and analyzed to determine fault features that can be used to monitor leakage at very initial stages (see Fig. 6). Compared to the pressure signal, the piston rod displacement signal was observed to be more sensitive when monitoring fluid leakage. Wavelet packet energy variance, pressure rising speed, wavelet energy value of level 4, piston rod stretching speed and wavelet packet energy entropy were proposed as features to monitor leakage. Wavelet packet energy variance was observed to be the most sensitive to fluid leakage in comparison to the other features. Tang *et al.* [104] applied the wavelet transforms and a backpropagation (BP) neural network to the pressure signal to monitor internal leakage in hydraulic cylinders. Energy of different frequency bands extracted from wavelet decomposition was constituted as eigenvectors. Then, the eigenvectors were given as input to a BP

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neural network. Using this technique, it was possible to separate no leakage, moderate leakage, and severe leakage conditions.

Goharrizi and Sepehri [105] studied the effectiveness of the Hilbert–Huang transform (HHT) technique for pressure signals for monitoring fluid leakage. The HHT technique uses the empirical mode decomposition (EMD) technique to decompose the signal into intrinsic mode functions (IMFs). The Hilbert transform was applied to the IMFs to extract instantaneous amplitudes and frequencies. The advantage of HHT over the wavelet technique is that it uses *a posteriori* basis function, which eliminates the need for selecting a mother wavelet [106]–[108]. To monitor the fluid leakage, the pressure signal was decomposed into IMFs using the EMD technique. To extract instantaneous amplitude, the Hilbert transform was applied to each IMF. Instantaneous magnitude of the first IMF was observed to be sensitive to internal fluid leakage. The proposed technique was sensitive to detect fluid leakage of 0.124 L/min during offline diagnosis and 0.23 L/min during online diagnosis [105].

Garimella and Yao [109], [110] used a nonlinear model-based adaptive robust observer (ARO) to diagnose lack of supply pressure in electro-hydraulic cylinders. Compared to traditional modeling techniques, the ARO technique uses the robust filter structures to reduce the effect of unmodeled dynamics and combines with online parameter adaption to reduce the effect of model uncertainty [111]. In the proposed fault detection scheme, the state estimation error was used to monitor lack of supply pressure. The state estimation errors at the rod and bottom ends of the cylinder were monitored for fault detection. When the state estimation error did not cross the threshold, it was defined as a fault case due to lack of system pressure [110].

In industry, a number of pressure sensors are commercially available that can be used to monitor pressure in hydraulic cylinders. For example, HYDAC [112] and Bosch Rexroth [113] offer pressure sensors based on different technologies such as conventional pressure transmitters, electronic pressure transducers, electronic pressure switches, and mechanical pressure switches. An electronic pressure transducer records the pressure and converts it into a proportional signal. An electronic pressure switch records the pressure, processes it, and sends the output in form of switching signals according to a predefined setting. A mechanical pressure switch converts the pressure of the fluid into a mechanical movement, which activates the mechanical switch that is in contact with pressure switch. SensorOne [114] offers a variety of pressure transducers that can sustain several 6.89 MPa and corrosive hydraulic fluids that is typically used in the aviation and automotive industries. Pressure sensors from PCB Piezotronics [115] contain integral machined diaphragms instead of thin diaphragms, which are susceptible to fatigue failure. These sensors can be used to monitor repetitive pulses that are normally observed in hydraulic applications.

B. Fluid Leakage Monitoring Using Accelerometer Sensors

A hydraulic cylinder shows several signs of inefficiency during leakage. These can be in the form of symptoms such change in the profiles of the chamber pressures, variation in vibrations,

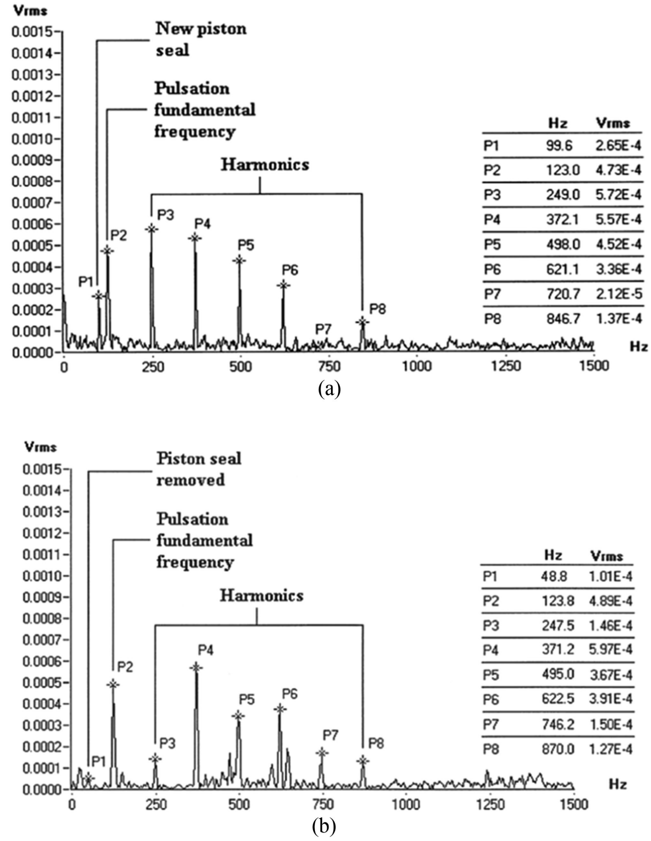

Fig. 7. Vibration-based amplitude-frequency spectrum at 40-kg load in cylinder. (a) With piston seal. (b) Without piston seal [116] (reproduced from [116] with permission from ASTM International).

noise, or fluid contamination. To monitor the change in vibration with leakage, Tan *et al.* [116], [117] and Yunbo *et al.* [118] monitored water leakage in water hydraulic cylinders using vibration sensors. Experiments were performed under varying loading conditions with a new piston seal and without a piston seal, to simulate the worn seal condition. Also, vibration energy (dBVrms) response was monitored by varying load conditions and piston seal wear. In the amplitude spectrum obtained from experiments with a new piston seal, a new amplitude peak at 99.6 Hz was observed, whereas in the amplitude spectrum obtained from experiments without piston seal, an amplitude peak at 48.8 Hz was present at all the loading conditions and the amplitude peak at 99.6 Hz was not observed (see Fig. 7). With an increase in loading conditions, the vibration energy (dBVrms) increased. This is mainly due to the instability in the movement of the piston rod of the cylinder, which results in an increase of dBVrms. However, with an increase in piston seal wear, dBVrms decreased, leading to increasing leakage over the piston seal. This leakage will create a liquid seal and makes the stroke smoother, resulting in reduction of dBVrms [117].

From the literature, it is known that vibration sensors can be used to diagnose fluid leakage in hydraulic cylinders. However, there is a need for additional investigation in an industrial environment as there may be noise involved from other sources surrounding the cylinder, such as the large seals of the radial

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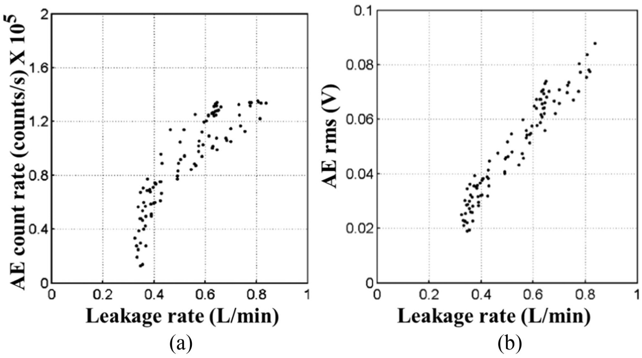

Fig. 8. Application of AE features to understand leakage in cylinders. (a) AE count rate. (b) RMS [15] (reproduced from [15] with permission from Elsevier).

gates in barriers. As the use of vibration sensors for fluid leakage monitoring from hydraulic cylinders is still in the research stage, the use of vibration-based condition monitoring of hydraulic cylinders is limited in the industry.

C. Fluid Leakage Monitoring Using AE Sensors

Condition monitoring of hydraulic cylinders using AE is another method for detecting internal leakage because AE signals are sensitive to local dynamical processes and are largely unaffected by machine noise because of its very high-frequency range [119]. Chen *et al.* [15], [120] monitored internal fluid leakage smaller than 1.0 L/min in water hydraulic cylinders using AE. Different features such as RMS, count, power spectral density (PSD), and energy were used to monitor leakage. The energy feature was observed to be highly sensitive to the internal leakage compared to the other features such as count rate and PSD. Also, a linear relationship was observed between the RMS and internal fluid leakage rate in a water hydraulic cylinder (see Fig. 8). In the PSD spectrum, the frequency due to internal fluid leakage was observed to be dominant in frequencies in the range of 50–300 kHz with a peak at 120 kHz. Shanbhag *et al.* [121], [122] monitored fluid leakage in a hydraulic test rig using an AE sensor. The feasibility of using time and frequency domain features to monitor fluid leakage due to a worn seal and a worn piston rod was investigated at varying speed and pressure conditions. Time-domain features such as RMS, kurtosis, skewness, peak, mean and frequency-domain features such as bandpower, mean frequency, and median frequency were used to analyze the AE signal. For the experiments performed at 100 mm/s [121], using skewness, bandpower, and mean frequency, it was possible to identify the nonleakage and fluid leakage conditions in the test rig. Using the mean frequency feature, it was also possible to identify the fluid leakage due to semiworn and worn seals. Also, the mean frequency feature showed a good repeatability and sensitivity for identifying the unworn and worn conditions of the rod under the nonleakage and fluid leakage conditions. For the experiments performed at 50 mm/s [122], only bandpower and PSD showed a good capability in identifying nonleakage condition, leakage due to semiworn and worn seal conditions. Due to the high sampling frequency of AE sensors, the size of data acquisition files is very large, and performing data analysis is time-consuming and computationally expensive. Therefore, there is a need for additional investigation to determine if the AE sensor can be used for the continuous monitoring of hydraulic cylinders in industries where the leakage occurs when the piston (rod) seal fails after considerable time.

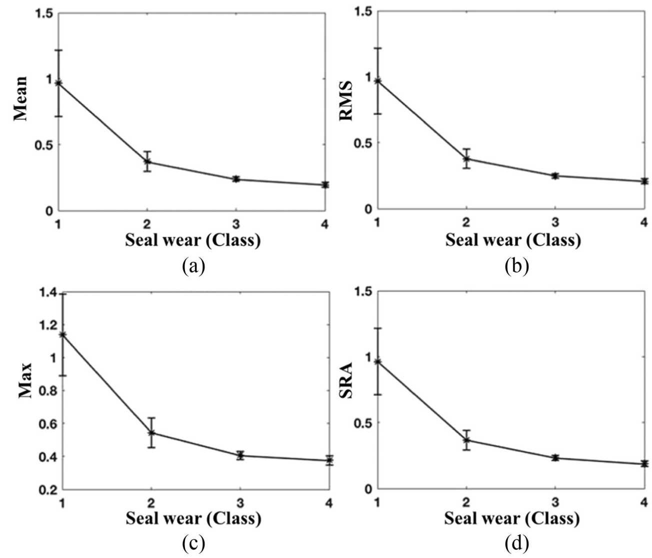

Fig. 9. Steady-state torque features for different seal wear conditions (a) Mean, (b) RMS, (c) Max, (d) SRA (Note: class 1: unworn, class 2: slightly worn, class 3: worn, class 4: failed. Reproduced from [123], as per Creative Commons Attribution 3.0 US license).

D. Fluid Leakage Monitoring Using Friction Torque Sensors

In recent times, friction torque sensors are used to monitor fluid leakage due to wear of rotary seals. Seal aging affects the mechanical properties of seals such as elastic modulus and hardness of the seal. The change in elastic modulus and hardness of seal results in lower interference between shafts and seals leading to fluid leakage [123]. Therefore, Ramachandran and Siddique [123], [124] used a friction torque sensor to monitor aging of rotary seals under accelerated testing conditions. Seals were aged using contaminated drilling fluid that consisted of clay, mica, silica, and barite. During aging, seals show signs of blisters, cracks or discoloration, and seal aging was immediately stopped when fluid leakage started. Using a friction torque sensor, breakout torque and steady-state torque were also studied. Breakout torque is defined as the total torque required to initiate relative motion between the rotary shaft and the seal, whereas steady-state torque is the torque when a machine is running at constant speed. From the breakout torque only, the peak value was extracted. From the steady-state torque, features such as mean, RMS, impulse factor, crest factor, shape factor, square mean rooted absolute amplitude (SRA), margin factor, standard deviation, kurtosis, and skewness were extracted. Torque features such as mean, RMS, peak, and SRA decreased with increase in seal aging (see Fig. 9), and impulse factor, crest factor, and margin factor increased with

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TABLE II
STATE-OF-THE-ART REVIEW ARTICLES DOCUMENTING STUDIES OF FLUID CONTAMINATION AND SENSORS THAT ARE COMMERCIALLY AVAILABLE IN THE MARKET FOR MONITORING FLUID CONTAMINATION

Methods	Principle	Literature	Commercially available sensor	Advantages
Electrical (Magnetic) methods	Dielectric constant	[50], [55] –[58]	[59]– [62]	• Can be used to identify fluid degradation features such as presence of water content in fluid, fluid viscosity, acid levels, change in temperature. • Low complexity in data processing and continuous online monitoring is possible.
	Conductivity	[66]–[68]	[69], [70]	• Can be used to identify fluid degradation features such as conductivity, permittivity, temperature, pressure and moisture content to determine contamination ingress and fluid aging. • Low complexity in data processing and continuous online monitoring is possible.
	Magnetic susceptibility	[72]–[74]	[75], [76]	• Can be used to identify ferrous and non-ferrous particles in the fluid. • Can be used to detect ferrous particles as low as ferrous particles as low as 1 μm and nonferrous particles of 150 μm and larger. • Can be used for real-time monitoring and also alerts operator at the early stages for corrective actions.
	Micro Acoustic viscosity	[78], [79]	[80]	• Can be used to identify fluid degradation features such as oxidation, water contamination, particle contaminants and fluid dilution. • Smaller in size compared to conventional mechanical and electromechanical viscometer. • Can be immersed in fluid because of its small size. • Unaffected by shock, vibration or flow conditions. Therefore, it can be used for harsh environments.
Optical methods	Optical transparency or reflectometry	[82]–[84]	[85]–[87]	• Can be used to identify fluid degradation and fluid contamination by monitoring color change parameters. Also, can be used to measure number of particles and size of particles. • Can be permanently mounted on the system and can be used for real - time monitoring.
	IR absorption	[89]–[91]	[92], [93]	• Can be used to identify fluid degradation features such as water content, soot content, antioxidant depletion, glycol contamination, sulphate, oxidation, nitration, phosphate, total acid number and total base number. • Handheld IR-based sensors are available. • Inline fluid monitoring is possible.

increasing seal aging. Therefore, these torque features have a strong potential to be used for monitoring fluid leakage due to seal wear under industrial conditions. However, the use of a friction torque sensor for fluid leakage monitoring from hydraulic cylinder is extremely limited as hydraulic cylinder involves linear movement. Therefore, there is a need for further investigation due to limited field experience with the torque sensor for monitoring fluid leakage in hydraulic cylinders.

E. Fluid Leakage Monitoring Using Data-Driven Methods

In recent times there is some progress made in implementing data-driven methods to develop real-time monitoring techniques for fluid leakage monitoring, or to identify different faults in hydraulic systems. For example, Ramachandran *et al.* [123], [125] implemented a neural network to monitor fluid leakage due to wear of rotary seals and used a hybrid-based method—particle swarm optimization (PSO) with support vector machine (SVM)—to monitor fluid leakage due to wear of reciprocating seals. For rotary seals, torque features such as RMS, peak, mean, and SRA were used as input for a multilayered perceptron neural network model (MLP-NN). The MLP-NN model was trained until the validation error rises with learning rate of 0.3 and a momentum of 0.2. A classification accuracy of 92.86% was obtained from this MLP-NN model. The classification accuracy of the MLP-NN model was higher when it was further compared with logistic and random forest classifiers [123]. For fault classification of reciprocating seals, features from force signals were used as input to the hybrid PSO-SVM model. As the seal degrades, maximum force during the compression cycle and maximum tension force during the tension cycle begin to increase. From the eight seals tested, an average correlation coefficient of 0.95 was found between the maximum tension force and run to failure time, which indicates that the maximum tension force can be used as an indicator to assess seal degradation. The results from hybrid the PSO-SVM model were compared with genetic algorithm (GA) SVM and optimized distributed gradient boosting system (XGBoost) using mean square error (MSE) and mean absolute error (MAE). MSE and MAE were lower for all seal conditions for the hybrid PSO-SVM model when compared to GA-SVM or XGBoost [125].

Helwig *et al.* [126] performed supervised classification based on linear discriminant analysis (LDA) with automated feature extraction and selection using a correlation coefficient criterion. Pressure, flow rate, vibration, electrical power, and temperature data were used for fault classification. The classification accuracy from the LDA technique was compared with artificial neural network (ANN), SVM (linear), and SVM [radial basis function (RBF)] for different parts of a hydraulic system (cooler, valve, pump, and accumulator). For the cooler classification, accuracy was 100% for all the techniques. For the valve, the classification accuracy was 100% for LDA, ANN, and SVM (linear), and 95.7% for the SVM (RBF) technique. For the pump, the classification accuracies were LDA-73.6%, ANN-80%, SVM (linear)-72.4%, and SVM (RBF)-64.2%. For the accumulator, the classification accuracies were LDA-54%, ANN-50.4%, SVM (linear)-51.6%, and SVM (RBF)-65.7%. To

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TABLE III
STATE-OF-THE-ART REVIEW ARTICLES DOCUMENTING STUDIES OF FLUID LEAKAGE DUE TO SEAL WEAR

Sensor	Paper	Technique	Features proposed	Advantages	Shortcomings
Pressure	[97]	EKF	Residual pressure error	• Can be used to detect internal fluid leakage, external fluid leakage, fluid leakage levels and lack of supply pressure. • Possible to correlate pressure signal with piston rod movement. • Fluid leakage as low as 0.124 L/min can be identified. • Pressure sensors are commercially available for hydraulic cylinders.	• Future work is required to identify pressure signal features that can indicate warning before leakage starts. • Feasibility of low complexity data processing techniques such as time and frequency domain features needs to be assessed.
	[47], [101], [102]	Wavelet Transform	For internal fluid leakage, RMS value of level two wavelet coefficient For external fluid leakage, RMS value of level four wavelet coefficient		
	[103]		Wavelet packet energy variance		
	[104]		Energy from frequency bands		
	[105]	HHT	Instantaneous magnitude of the first IMF		
	[109], [110]	ARO	State estimation error		
Vibration	[116]–[118]	Time-domain and frequency-domain features	dBVrms	• Can be used to detect fluid leakage due to seal wear. • Low complexity in data processing as time and frequency domain features can be used to study seal wear.	• Feasibility of the technique to identify seal wear under different noise conditions (rod or bearing failure) needs to be assessed. • Commercially not available as the vibration-based condition monitoring technique is still under research stage for hydraulic cylinders.
AE	[15]		RMS	• Can be used to detect fluid leakage due to seal wear. • Can be used to identify other defects in hydraulic cylinders such as piston rod wear during fluid leakage conditions. • Internal fluid leakage smaller than 1.0 L/min can be monitored. • Low complexity in data processing as time and frequency domain features can be used to study seal wear.	• Requires large data space for continuous AE signal data acquisition. • Future work is required to identify AE signal features that can indicate warning before leakage starts. • Commercially not available as the AE-based condition monitoring technique is still under research stage for hydraulic cylinders.
	[121], [122]		Mean frequency at 100mm/s, bandpower and PSD at 50mm/s		
Friction torque	[123], [124]	Time-domain features	Mean, RMS, peak and SRA	• Low complexity in data processing as time-domain features can be used to study seal wear and seal aging.	• Future work is required to identify friction torque signal features that can indicate warning before leakage starts. • Commercially not available as the torque-based condition monitoring technique is still under research stage for hydraulic cylinders.
Force	[125]	SVM-PSO technique	Maximum tension force	• Fluid leakage less than 0.2 mL can be monitored. • Real-time monitoring of fluid leakage is possible. • Possible to correlate force signal with extension and retraction cycle.	• Feasibility of low complexity data processing techniques such as time and frequency domain features needs to be assessed. • Commercially not available as the force-based condition monitoring technique is still under research stage for hydraulic cylinders.

improve the classification accuracy, Chawte [127] replaced the time series with features such as mean, variance, skewness and kurtosis. After the feature extraction, data classification was performed using different algorithms such as ZeroR, OneR, JRip, PART, J48, random forest, and the Naive Bayes technique. Classification accuracy of the algorithms was measured using three techniques such as percentage, area under receiver operating characteristics curve, and kappa statistic. Compared to all algorithms, random forest provides high classification accuracy (>99%) followed by the J48 algorithm for all the parts in the hydraulic system. Methodology of machine learning techniques developed by Ramachandran *et al.* [123], [125], Helwig *et al.* [126], and Chawathe [127] can be further improved by implementing them specifically for hydraulic cylinders to classify faults such as seal wear, rod wear, and fluid contamination.

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V. Discussion

A. Fluid Contamination

A review of the state of the art in the area of condition monitoring of hydraulic cylinders revealed numerous methods to identify different types of fluid contaminants. A detailed summary of the literature that has studied fluid contamination and sensors that are commercially available are presented in Table II. In general, the literature demonstrates the capability of each method to identify different fluid contaminants such as water content in fluid, metallic debris, and fluid aging (see Table II). Fluid contamination strongly depends on physical and chemical properties of the fluid [128], [129]. Therefore, for hydraulic cylinders, it is important to select the sensors based on factors such as application, usage and harshness of the working environment. Using multiple sensors for hydraulic cylinders based on different principles will help in smart monitoring as they will cover a wide area of defects. Use of sensors based on, e.g., dielectric constant, magnetic susceptibility, and IR absorption will help monitoring almost all defects such as change in viscosity, water content, metallic debris, fluid aging, total acid number, and the total base number. While monitoring fluid contaminants, it is also important to monitor RUL of the fluid. Therefore, in these days, many industries are providing remote monitoring of fluid contamination for their clients to eliminate unplanned maintenance [62], [76]. Also, new technologies are developed to minimize the size of the sensors. For example, microacoustic sensors are very small and can be immersed in the fluid. These sensors are not affected by shock, vibration, or flow conditions. Normally a different data acquisition and processing system is required for each type of sensor. Thus, there is a need for further research to develop a module-based approach that works on multiple principles for detecting change in parameters or features that announces upcoming defects. For example, the fluid monitoring module from HYDAC [130] combines a contamination sensor and an aqua sensor into one module. This module can detect solid particle contaminants, water content and fluid conditions such as relative change in the electrical conductivity and the dielectric constant. These kinds of modules that work on multiple principles, may be the future of fluid deterioration monitoring, diagnostics and prognostics.

B. Fluid Leakage

Numerous condition monitoring techniques based on different sensors have been proposed in the literature to monitor fluid leakage. A detailed summary of research works that have studied fluid leakage and the signal processing techniques developed for analyzing sensor data are presented in Table III. The literature demonstrates a capability from sensor-based condition monitoring techniques to identify fluid leakage as low as 0.124 L/min and also sensor-based features that can be used to continuously monitor seal wear in hydraulic cylinders. Fluid leakage from hydraulic cylinders is dependent on a number of factors such as seal wear, rod damage and fluid contamination. In literature, using pressure, vibration, AE, torque, and force, it has been demonstrated that it is possible to monitor fluid leakage in hydraulic cylinders due to seal wear. Shanbhag *et al.* [121], [122] demonstrated the capability of AE sensing to monitor the unworn and worn piston rod conditions under nonleakage and fluid leakage conditions. Also, the capability of torque sensors to monitor seal wear was demonstrated by Ramachandran and Siddique [124]. Sensor-based features (time and frequency domain) demonstrated in [15], [116], [121], [122], and [124] involves low complexity in data processing. Therefore, it represents a promising approach on further work toward continuous monitoring of seal wear under industrial conditions and to develop prognostic-based models to determine RUL of the seal from the point where the seal starts to degrade.

VI. Conclusion

This article has presented a state-of-the-art review of condition monitoring studies performed to diagnose fluid contamination and fluid leakage in hydraulic cylinder, along with selected commercially available monitoring systems. Different condition monitoring parameters that can be used to monitor fluid contamination and fluid leakage are discussed. According to this state-of-the-art review, the following statements hold.

1) For fluid contamination monitoring, sensors based on the principle of the dielectric constant, magnetic susceptibility, and IR absorption will help in monitoring almost all the defects that are commonly observed, such as change in viscosity, water content, metallic debris, fluid aging, change in total acid number and change in total base number.
2) Fluid monitoring modules that work on multiple principles to detect multiple defects are promising condition monitoring technologies for fluid contamination monitoring since they can monitor critical parameters such as solid particle contaminants, water content and fluid conditions such as relative change in electrical conductivity and the dielectric constant. As an ultimate solution, the monitoring is integrated in an inline fluid reconditioning system.
3) Using pressure, vibration, AE, and torque, it is possible to diagnose fluid leakage due to seal wear. Fluid leakage as low as 0.124 L/min can successfully be detected using the sensor-based condition monitoring approaches.
4) Sensor-based time domain and frequency domain features have the capability to continuously monitor fluid leakage due to seal wear. The RMS feature has shown the capability to monitor fluid leakage from pressure, vibration, AE, and torque data.

If sensors based on dielectric constant, magnetic susceptibility, and IR absorption principle are used along with sensors that can be used to monitor fluid leakage (pressure/vibration/torque/AE) then together they can form a promising smart condition monitoring system to overcome existing challenges by monitoring and separating multiple simultaneous defects, and will probably be the future technology for online diagnostics and prognostics of hydraulic cylinders.

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References

[1] J. Mattila, J. Koivumaki, D. G. Caldwell, and C. Semini, "A survey on control of hydraulic robotic manipulators with projection to future trends," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 2, pp. 669–680, Apr. 2017.

[2] B. Yao, F. Bu, J. Reedy, and G.-C. Chiu, "Adaptive robust motion control of single-rod hydraulic actuators: Theory and experiments," *IEEE/ASME Trans. Mechatronics*, vol. 5, no. 1, pp. 79–91, Mar. 2000.

[3] N. A. Peppiatt and B. Flitney, "International standards for reciprocating seals used in hydraulic applications," *Sealing Technol.*, vol. 2004, pp. 7–10, 2004, doi: 10.1016/S1350-4789(04)00270-3.

[4] R. Adnan, M. Tajjudin, N. Ishak, H. Ismail, and M. H. Fazalul Rahiman, "Self-tuning fuzzy PID controller for electro-hydraulic cylinder," in *Proc. IEEE 7th Int. Colloq. Signal Process. Appl.*, 2011, pp. 395–398.

[5] "Hydraulic cylinder market," Accessed: May 22, 2020. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/hydraulic-cylinders-market-252743122.html

[6] *Hydraulic Fluid Power—Cylinders—Dimensions and Tolerances of Housings for Single-Acting Piston and Rod Seals in Reciprocating Applications*, ISO 5597:2018, 2018. [Online]. Available: https://www.iso.org/standard/74704.html

[7] S. M. Gonzalo A. Barillas, S. Cowell, M. Goerres, W. Lipphardt, and U. Siegrist, "Sealing systems for hydraulic cylinders," in *Proc. 11th Int. Fluid Power Conf.*, 2018, pp. 283–293. [Online]. Available: http://publications.rwth-aachen.de/record/726053/files/726053.pdf

[8] L. F. Schexnayder, "Contaminant removal from a hydraulic cylinder," U.S. Patent 3 943 717, Mar. 16, 1976.

[9] L. Lloyd, "Hydraulic system leakage—The destructive drip," *Machinery Lubrication*, 2000. Accessed: May 22, 2020. [Online]. Available: https://www.machinerylubrication.com/Read/21/hydraulic-system-leakage

[10] "Minimizing the risk of hydraulic cylinder contamination," *Agressive Hydraulics*, 2020. Accessed on: Sep. 14, 2020. [Online]. Available: https://www.aggressivehydraulics.com/minimizing-the-risk-of-hydraulic-cylinder-contamination/

[11] K. Korane, "How do hydraulic cylinders fail—contamination," Mobile Hydraulic Tips, 2015. Accessed: Sep. 14, 2020. [Online]. Available: https://www.mobilehydraulictips.com/how-do-hydraulic-cylinders-fail-contamination/

[12] M. Singh, G. S. Lathkar, and S. K. Basu, "Failure prevention of hydraulic system based on oil contamination," *J. Inst. Engineers India Ser. C*, vol. 93, pp. 269–274, 2012, doi: 10.1007/s40032-012-0032-2.

[13] *Vickers Industrial Hydraulics Manual*, 2nd ed., Nashville, TN, USA: Vickers, 1989.

[14] A. Bruederle and R. Hodler, "Effect of oil spills on infant mortality in Nigeria," *Proc. Nat. Acad. Sci. USA*, vol. 116, no. 12, pp. 5467–5471, 2019.

[15] P. Chen, P. S. K. Chua, and G. H. Lim, "A study of hydraulic seal integrity," *Mech. Syst. Signal Process.*, vol. 21, pp. 1115–1126, 2007, doi: 10.1016/j.ymssp.2005.09.002.

[16] J. Luo, K. R. Pattipati, L. Qiao, and S. Chigusa, "Model-based prognostic techniques applied to a suspension system," *IEEE Trans. Syst., Man, Cybern., A, Syst. Humans*, vol. 38, no. 5, pp. 1156–1168, Sep. 2008.

[17] W. Wang and O. A. Jianu, "A smart sensing unit for vibration measurement and monitoring," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 1, pp. 70–78, Feb. 2010.

[18] T. Xi, S. Kehne, T. Fujita, A. Epple, and C. Brecher, "Condition monitoring of ball-screw drives based on frequency shift," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 3, pp. 1211–1219, Jun. 2020.

[19] K. Kim and A. G. Parlos, "Induction motor fault diagnosis based on neuropredictors and wavelet signal processing," *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 201–219, Jun. 2002.

[20] R. Orsagh, H. Lee, and M. Watson, "Advanced vibration monitoring for wind turbine health management," *Impact Technol.*, 2006.

[21] P. Tchakoua, R. Wamkeue, M. Ouhrouche, F. Slaoui-Hasnaoui, T. A. Tameghe, and G. Ekemb, "Wind turbine condition monitoring: State-of-the-art review, new trends, and future challenges," *Energies*, vol. 7, pp. 2595–2630, 2014, doi: 10.3390/en7042595.

[22] I. El-Thalji, I. Alsyouf, and G. Ronsten, "A model for assessing operation and maintenance cost adapted to wind farms in cold climate environment: Based on onshore and offshore case studies," in *Proc. Eur. Offshore Wind Conf.*, 2009, pp. 1–10.

[23] J. Koochaki, J. Bokhorst, H. Wortmann, and W. Klingenberg, "Evaluating condition based maintenance effectiveness for two processes in series," *J. Qual. Maintenance Eng.*, vol. 17, pp. 398–414, 2011, doi: 10.1108/13552511111180195.

[24] Pragmatic Maintenance and Reliability, "How to save more money with condition monitoring," 2012. Accessed: May 23, 2020. [Online]. Available: http://www.pmar.co.uk/PMAR_Back_to_Basics_Pt1.pdf

[25] S. Barber and P. Golbeck, "Wind turbine maintenance & condition monitoring," *World Wind Energy Assoc.*, Bonn, Germany, 2006.

[26] D. Baglee, M. Knowles, S.-K. Kinnunen, and D. Galar, "A proposed maintenance strategy for a wind turbine gearbox using condition monitoring techniques," *Int. J. Process Manag. Benchmarking*, vol. 6, no. 3, pp. 386–403, 2016.

[27] Norwegian Petroleum, "Investment and operating cost," 2021. Accessed: May 22, 2020. [Online]. Available: https://www.norskpetroleum.no/en/economy/investments-operating-costs/

[28] T. Abbasi, K. H. Lim, T. A. Soomro, I. Ismail, and A. Ali, "Condition based maintenance of oil and gas equipment: A review," in *Proc. 3rd Int. Conf. Comput., Math. Eng. Technol.*, 2020, pp. 1–9. doi: 10.1109/iCoMET48670.2020.9073819.

[29] E. Jantunen, "A summary of methods applied to tool condition monitoring in drilling," *Int. J. Mach. Tools Manuf.*, vol. 42, pp. 997–1010, 2002, doi: 10.1016/S0890-6955(02)00040-8.

[30] K. P. Zhu, Y. S. Wong, and G. S. Hong, "Wavelet analysis of sensor signals for tool condition monitoring: A review and some new results," *Int. J. Mach. Tools Manuf.*, vol. 49, pp. 537–553, 2009, doi: 10.1016/j.ijmachtools.2009.02.003.

[31] "Hydraulic cylinder failure solutions," MAC Hydraulics, 2019. Accessed: Sep. 14, 2020. [Online]. Available: https://mac-hyd.com/blog/hydraulic-cylinder-failure-solutions/

[32] J. Zhu, D. He, and E. Bechhoefer, "Survey of lubrication oil condition monitoring, diagnostics, and prognostics techniques and systems," *J. Chem. Sci. Technol.*, vol. 2, no. 3, pp. 100–115, 2013.

[33] B. C. Sharma and O. P. Gandhi, "Performance evaluation and analysis of lubricating oil using parameter profile approach," *Ind. Lubrication Tribol.*, vol. 60, pp. 131–137, 2008, doi: 10.1108/00368790810871057.

[34] Noria Corporation, "Water in oil contamination," Machinery Lubrication, 2001. Accessed: May 24, 2020. [Online]. Available: https://www.machinerylubrication.com/Read/192/water-contaminant-oil

[35] M. Day and C. Bauer, "Water contamination in hydraulic and lube systems," *Pract. Oil Anal.*, vol. 9, pp. 1–9, 2007.

[36] Y. Du, T. Wu, and R. Gong, "Properties of water-contaminated lubricating oil: Variation with temperature and small water content," *Tribol.—Mater. Surf. Interfaces*, vol. 11, pp. 1–6, 2017, doi: 10.1080/17515831.2017.1279845.

[37] W. D. Phillips and J. W. G. Staniewski, "The origin, measurement and control of fine particles in non-aqueous hydraulic fluids and their effect on fluid and system performance," *Lubrication Sci.*, vol. 28, pp. 43–64, 2016, doi: 10.1002/ls.1300.

[38] B. Battat and W. Babcock, "Reducing the effects of contamination on hydraulic fluids and systems," *Pract. Oil Anal.*, 2006. Accessed: May 24, 2020. [Online]. Available: https://www.machinerylubrication.com/Read/957/hydraulic-fluids-contamination

[39] B. Casey, "Defining and maintaining fluid cleanliness for maximum hydraulic component life," 2011. Accessed: May 24, 2020. [Online]. Available: http://total-productive-maintenance.com/articles/hydraulic_fluid_cleanliness.pdf

[40] Eaton, "The systematic approach to contamination control," 2002. Accessed: May 24, 2020. [Online]. Available: https://www.eaton.com/ecm/groups/public/@pub/@eaton/@hyd/documents/content/ct_233707.pdf

[41] M. Orošnjak, T. Peković, M. Jocanović, V. Karanović, and A. H. Novak, "Using contamination control in condition based maintenance of a hydraulic system," in *Proc. 42nd Forum Maintenance Asset Manage.*, 2017, pp. 102–111.

[42] J. T. Burwell Jr., "Survey of possible wear mechanisms," *Wear*, vol. 1, no. 2, pp. 119–141, 1957.

[43] H. Michael, "Lubricant failure mechanisms," Jet Lube, 2020. [Online]. Available: https://www.jetlube.com/blog/lubricant-failure-mechanisms#

[44] F. Ng, J. A. Harding, and J. Glass, "Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring," *Mech. Syst. Signal Process.*, vol. 83, pp. 176–193, 2017, doi: 10.1016/j.ymssp.2016.06.006.

Authorized licensed use limited to: Hochschule HS Furtwangen. Downloaded on July 02,2025 at 10:24:12 UTC from IEEE Xplore. Restrictions apply.

[45] Noria Corporation, "The importance of oil oxidation stability," *Machinery Lubrication*, Accessed: May 24, 2020. [Online]. Available: https://www.machinerylubrication.com/Read/28966/oil-oxidation-stability

[46] X. Wu, Y. Li, F. Li, Z. Yang, and W. Teng, "Adaptive estimation-based leakage detection for a wind turbine hydraulic pitching system," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 5, pp. 907–914, Oct. 2012.

[47] A. Y. Goharrizi and N. Sepehri, "A wavelet-based approach for external leakage detection and isolation from internal leakage in valve-controlled hydraulic actuators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 9, pp. 4374–4384, Sep. 2011.

[48] S. J. Shen and Q. H. Yang, "Analysis and solution of hydraulic cylinder's leakage problem," *Adv. Mater. Res.*, vol. 189–193, pp. 664–667, 2011, doi: 10.4028/www.scientific.net/AMR.189-193.664.

[49] C. Gonzalez, "7 common failures of hydraulic seals," Mach. Des., 2017.

[50] S. Raadnui and S. Kleesuwan, "Low-cost condition monitoring sensor for used oil analysis," *Wear*, vol. 259, pp. 1502–1506, 2005, doi: 10.1016/j.wear.2004.11.009.

[51] Bosch Rexroth, "Oil treatment system VacuClean VCM," 2020. Accessed: Oct. 14, 2020. [Online]. Available: https://www.boschrexroth.com/ics/cat/?cat=Industrial-Hydraulics-Catalog&m=XC&u=si&o=Desktop&p=p770960&pi=19554B77-AC93-766E-7C71A1D45BEEEFA9_ICS_82

[52] J. Zhu, J. M. Yoon, D. He, Y. Qu, and E. Bechhoefer, "Lubrication oil condition monitoring and remaining useful life prediction with particle filtering," *Int. J. Prognostics Health Manage.*, vol. 4, pp. 1–15, 2013.

[53] J. D. Turner and L. Austin, "Electrical techniques for monitoring the condition of lubrication oil," *Meas. Sci. Technol.*, vol. 14, pp. 1794–1800, 2003, doi: 10.1088/0957-0233/14/10/308.

[54] A. A. Carey and A. J. Hayzen, "The dielectric constant and oil analysis," *Pract. Oil Anal. Mag.*, vol. 9, pp. 1–5, 2001.

[55] Y. Dingxin, Z. Xiaofei, H. Zheng, and Y. Yongmin, "Oil contamination monitoring based on dielectric constant measurement," in *Proc. Int. Conf. Meas. Technol. Mechatronics Autom.*, 2009, pp. 249–252, doi: 10.1109/ICMTMA.2009.588.

[56] Y. Liu, Z. Liu, Y. Xie, and Z. Yao, "Research on an on-line wear condition monitoring system for marine diesel engine," *Tribol. Int.*, vol. 33, pp. 829–835, 2000, doi: 10.1016/S0301-679X(00)00128-6.

[57] L. Guan, X. L. Feng, G. Xiong, and J. A. Xie, "Application of dielectric spectroscopy for engine lubricating oil degradation monitoring," *Sensors Actuators A, Phys.*, vol. 168, pp. 22–29, 2011, doi: 10.1016/j.sna.2011.03.033.

[58] C. Ulrich, H. Petersson, H. Sundgren, F. Björefors, and C. Krantz-Rülcker, "Simultaneous estimation of soot and diesel contamination in engine oil using electrochemical impedance spectroscopy," *Sensors Actuators B, Chem.*, vol. 127, pp. 613–618, 2007, doi: 10.1016/j.snb.2007.05.014.

[59] Parker, "Oil condition sensor," Accessed: May 26, 2020. [Online]. Available: https://www.parker.com/literature/Hydraulic Filter Division Europe/Websphere Literature/OIL_CONDITION_SENSOR.pdf

[60] HYDAC, "Oil condition sensors," Accessed: May 26, 2020. [Online]. Available: https://www.hydac.com/de-en/products/sensors/oil-condition-sensors.html

[61] CM Technologies, "Combined oil condition & moisture sensor," Accessed: May 26, 2020. [Online]. Available: https://www.cmtechnologies.de/en/products-en/oil-condition/oil-sensors/oil-condition-sensor.html

[62] Poseidon Systems, "Oil quality and water contamination monitor," Accessed: May 26, 2020. [Online]. Available: https://servintel.com/es/productos/140-Poseidon_Systems/141-Inline_Oil_Quality_Sensors/P640-oil-quality-and-water-contamination-monitor-trident-qw3100

[63] M. Mauntz, U. Kuipers, and J. Gegner, "New electric online oil condition monitoring sensor—An innovation in early failure detection of industrial gears," in *Proc. Int. Multi-Conf. Eng. Technol. Innov.*, 2011, pp. 238–242.

[64] *Standard Test Methods for Electrical Conductivity of Aviation and Distillate Fuels*, ASTM D2624-15, 2015.

[65] M. Lindner, "Oil condition monitoring using electrical conductivity," Machinery Lubrication, 2013. Accessed: May 26, 2020. [Online]. Available: https://www.machinerylubrication.com/Read/29407/oil-condition-monitoring

[66] S. I. Moon, K. K. Paek, Y. H. Lee, J. K. Kim, S. W. Kim, and B. K. Ju, "Multiwall carbon nanotube sensor for monitoring engine oil degradation," *Electrochem. Solid-State Lett.*, vol. 9, pp. H78–H80, 2006, doi: 10.1149/1.2209433.

[67] A. Basu *et al.*, "'Smart sensing' of oil degradation and oil level measurements in gasoline engines," *SAE Trans.*, vol. 109, pp. 857–863, 2000.

[68] J. C. Fitch, "Control and management of particle contamination in hydraulic fluids," in *Handbook of Hydraulic Fluid Technology*, 2nd ed., Boca Raton, FL, USA: CRC Press, 2011.

[69] Argo Hytos, "Lubrication condition sensor," Accessed: May 27, 2020. [Online]. Available: https://www.argo-hytos.com/en/products/sensors-measurement/lubrication-condition-sensors/lubcos-level.html

[70] Parker, "Online fluid condition sensor," Accessed: May 26, 2020. [Online]. Available: https://ph.parker.com/us/en/online-fluid-condition-sensor-fcs

[71] J. Fitch, "The rationale for using magnetic particle collectors," Machinery Lubrication, 2009. [Online]. Available: https://www.machinerylubrication.com/Read/2466/rationale-for-using-magnetic-particle-collectors

[72] J. D. Halderman and C. D. Mitchell, *Automotive Brake Systems*. Upper Saddle River, NJ, USA: Prentice-Hall, 1996.

[73] H. X. Tian, C. H. Zhang, and Y. L. Sun, "Development of sensor to monitor ferromagnetic debris based on electromagnetic induction principle," *Appl. Mechanics Mater.*, vol. 336–338, pp. 388–391, 2013, doi: 10.4028/www.scientific.net/AMM.336-338.388.

[74] L. Du and J. Zhe, "A high throughput inductive pulse sensor for online oil debris monitoring," *Tribol. Int.*, vol. 44, pp. 175–179, 2011, doi: 10.1016/j.triboint.2010.10.022.

[75] Kittiwake, "Total ferros debris sensor," Accessed: May 27, 2020. [Online]. Available: https://www.optimus.be/brochures/FG-K16344-KW.pdf

[76] Poseidon Systems, "Inline wear debris sensor," Accessed: May 27, 2020. [Online]. Available: https://www.poseidonsys.com/products-and-services/products/inline-wear-debris/

[77] SenGenuity, "Oil and fuel monitoring using the ViSmart viscosity sensor," Accessed: May 27, 2020. [Online]. Available: https://www.machinerylubrication.com/Read/2071/oil-fuel-viscosity-sensor

[78] B. Jakoby, F. P. Klinger, and P. Svasek, "A novel microacoustic viscosity sensor providing integrated sample temperature control," *Sensors Actuators A, Phys.*, vol. 123–124, pp. 274–280, 2005, doi: 10.1016/j.sna.2005.03.024.

[79] A. Agoston, C. Ötsch, and B. Jakoby, "Viscosity sensors for engine oil condition monitoring—Application and interpretation of results," *Sensors Actuators A, Phys.*, vol. 121, pp. 327–332, 2005, doi: 10.1016/j.sna.2005.02.024.

[80] Vectron International, "Monitoring oil viscosity in machine tools using ViSmart Viscosity sensor," Accessed: May 27, 2020. [Online]. Available: https://www.all-electronics.de/wp-content/uploads/migrated/document/114341/412-monitoring-oil-viscosity-in-machine-tools-using-vismart-viscosity-sensor-1.pdf

[81] A. Villar, A. Gorritxategi, E. Alarcón, and J. Arnaiz, "Low cost on-line sensors for condition monitoring of lubricating oil," Maintworld, 2012.

[82] S. Kumar, P. S. Mukherjee, and N. M. Mishra, "Online condition monitoring of engine oil," *Ind. Lubrication Tribol.*, vol. 57, pp. 260–267, 2005, doi: 10.1108/00368790510622362.

[83] C. V. Ossia, K. Hosung, and L. V. Markova, "Utilization of color change in the condition monitoring of synthetic hydraulic oils," *Ind. Lubrication Tribol.*, vol. 62, pp. 349–355, 2010, doi: 10.1108/00368791011076245.

[84] P. Lopez, J. Mabe, G. Miró, and L. Etxeberria, "Low cost photonic sensor for in-line oil quality monitoring: Methodological development process towards uncertainty mitigation," *Sensors*, vol. 18, 2018, Art. no. 2015, doi: 10.3390/s18072015.

[85] HYDAC, "Contamination sensor," Accessed: May 28, 2020. [Online]. Available: https://www.hydac.com/de-en/service/fluid-engineering/condition-monitoring/product-program/sensors.html

[86] IFM Electronic, "Oil particle monitor," Accessed: May 28, 2020. [Online]. Available: https://www.ifm.com/gb/en/product/LDP100

[87] Bosch Rexroth, "Online particle monitor OPM II," Accessed: Oct. 13, 2020. [Online]. Available: https://www.boschrexroth.com/ics/cat/?cat=Industrial-Hydraulics-Catalog&m=XC&u=si&o=Desktop&p=p676645&pi=638E7F61-905B-3AC6-665B8D4EA19272C2_ICS_82

[88] A. Geach, "Infrared analysis as a tool for assessing degradation in used engine lubricants," *Wearcheck Tech. Bull.*, no. 2, 1996.

[89] A. Agoston, C. Ötsch, J. Zhuravleva, and B. Jakoby, "An IR-absorption sensor system for the determination of engine oil deterioration," in *Proc. IEEE SENSORS*, 2004, pp. 463–466.

[90] M. S. Rauscher, A. J. Tremmel, M. Schardt, and A. W. Koch, "Non-dispersive infrared sensor for online condition monitoring of gearbox oil," *Sensors*, vol. 17, 2017, Art. no. 399, doi: 10.3390/s17020399.

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[91] T. Bley, E. Pignanelli, and A. Schütze, “Multi-channel IR sensor system for determination of oil degradation,” *J. Sensors Sensor Syst.*, vol. 3, pp. 121–132, 2014, doi: 10.5194/jsss-3-121-2014.

[92] CM Technologies, “IR analyser,” 2020. Accessed: May 29, 2020. [Online]. Available: https://www.cmtechnologies.de/images/catalogue/catalogue.html#8

[93] ZILA, “Oil condition monitoring,” 2019. Accessed: May 29, 2020. [Online]. Available: https://www.zila.de/images/Datenblaetter/data_sheet_Lub-6.pdf

[94] N. Peppiatt, “The influence of the rod wiper on the leakage from a hydraulic cylinder gland,” *Sealing Technol.*, vol. 2003, pp. 5–8, 2003, doi: 10.1016/S1350-4789(03)00014-X.

[95] K. Slater, “Detecting and managing hydraulic system leakage,” Machinery Lubrication, 2001.

[96] “Hydraulic fluid leaks,” MAC Hydraulics, 2019. Accessed: Jun. 2, 2020. [Online]. Available: https://mac-hyd.com/blog/hydraulic-fluid-leaks/

[97] L. An and N. Sepehri, “Hydraulic actuator leakage fault detection using extended Kalman filter,” *Int. J. Fluid Power*, vol. 6, pp. 41–51, 2005, doi: 10.1080/14399776.2005.10781210.

[98] I. Daubechies, *Ten Lectures on Wavelets*. Philadelphia, PA, USA: SIAM, 1992.

[99] I. S. Cade, P. S. Keogh, and M. N. Sahinkaya, “Fault identification in rotor/magnetic bearing systems using discrete time wavelet coefficients,” *IEEE/ASME Trans. Mechatronics*, vol. 10, no. 6, pp. 648–657, Dec. 2005.

[100] M. Ourak, B. Tamadazte, O. Lehmann, and N. Andreff, “Direct visual servoing using wavelet coefficients,” *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 3, pp. 1129–1140, Jun. 2019.

[101] A. Y. Goharrizi and N. Sepehri, “A wavelet-based approach to internal seal damage diagnosis in hydraulic actuators,” *IEEE Trans. Ind. Electron.*, vol. 57, no. 5, pp. 1755–1763, May 2010.

[102] A. Y. Goharrizi, N. Sepehri, and Y. Wu, “A wavelet-based approach for diagnosis of internal leakage in hydraulic actuators using online measurements,” *Int. J. Fluid Power*, vol. 11, pp. 61–69, 2010, doi: 10.1080/14399776.2010.10780998.

[103] X. Zhao, S. Zhang, C. Zhou, Z. Hu, R. Li, and J. Jiang, “Experimental study of hydraulic cylinder leakage and fault feature extraction based on wavelet packet analysis,” *Comput. Fluids*, vol. 106, pp. 33–40, 2015.

[104] H. Tang, Y. Wu, and C. Ma, “Inner leakage fault diagnosis of hydraulic cylinder using wavelet energy,” *Adv. Mater. Res.*, vol. 139–141, pp. 2517–2521, 2010, doi: 10.4028/www.scientific.net/AMR.139-141.2517.

[105] A. Y. Goharrizi and N. Sepehri, “Internal leakage detection in hydraulic actuators using empirical mode decomposition and Hilbert spectrum,” *IEEE Trans. Instrum. Meas.*, vol. 61, no. 2, pp. 368–378, Feb. 2012.

[106] N. E. Huang *et al.*, “The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis,” *Proc. Roy. Soc. A, Math. Phys. Eng. Sci.*, vol. 454, pp. 903–995, 1998.

[107] Z. K. Peng, P. W. Tse, and F. L. Chu, “A comparison study of improved Hilbert-Huang transform and wavelet transform: Application to fault diagnosis for rolling bearing,” *Mech. Syst. Signal Process.*, vol. 19, pp. 974–988, 2005, doi: 10.1016/j.ymssp.2004.01.006.

[108] E. T. Esfahani, S. Wang, and V. Sundararajan, “Multisensor wireless system for eccentricity and bearing fault detection in induction motors,” *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 3, pp. 818–826, Jun. 2014.

[109] P. Garimella and B. Yao, “Nonlinear adaptive robust observer for velocity estimation of hydraulic cylinders using pressure measurement only,” in *Proc. Int. Mech. Engineers Congr. Expo.*, 2002, Paper IMECE2002-32077, doi: 10.1115/IMECE2002-32077.

[110] P. Garimella and B. Yao, “Model based fault detection of an electrohydraulic cylinder,” in *Proc. Amer. Control Conf.*, 2005, pp. 484–489, doi: 10.1109/acc.2005.1469982.

[111] P. Garimella and B. Yao, “Nonlinear adaptive robust observer design for a class of nonlinear systems,” in *Proc. Amer. Control Conf.*, 2003, pp. 4391–4396, doi: 10.1109/acc.2003.1240530.

[112] HYDAC, “Pressure sensors,” Accessed: Jun. 3, 2020. [Online]. Available: https://www.hydac.com/de-en/products/sensors/pressure-sensors.html

[113] Bosch Rexroth, “Oil measurement technology,” Accessed: Oct. 13, 2020. [Online]. Available: https://www.boschrexroth.com/ics/cat/?id=&cat=Industrial-Hydraulics-Catalog&p=g253891

[114] SensorsOne, “Hydraulic analog voltage signal pressure transducers,” Accessed: Jun. 3, 2020. [Online]. Available: https://www.sensorsone.com/hydraulic-analog-voltage-signal-pressure-transducers/

[115] PCB Pizeotronics, “Industrial grade hydraulic & pneumatic pressure sensors,” Accessed on: Jun. 3, 2020. [Online]. Available: https://www.pcb.com/sensors-for-test-measurement/pressure-transducers/hydraulic-pneumatic

[116] A. C. H. Tan, P. S. K. Chua, and G. H. Lim, “Condition monitoring of a water hydraulic cylinder by vibration analysis,” *J. Test. Eval.*, vol. 28, no. 6, pp. 507–512, 2000.

[117] A. C. H. Tan, P. S. K. Chua, and G. H. Lim, “Fault diagnosis of water hydraulic actuators under some simulated faults,” *J. Mater. Process. Technol.*, vol. 138, pp. 123–130, 2003, doi: 10.1016/S0924-0136(03)00060-8.

[118] H. Yunbo, G. Lim, P. Chua, and A. Tan, “Monitoring the condition of loaded modern water hydraulic axial piston motor and cylinder,” in *Proc. 5th Int. Conf. Fluid Power Transmiss. Control*, 2001, pp. 447–451.

[119] R. K. Miller and P. McIntire, *Nondestructive Testing Handbook: Acoustic Emission Testing*. Columbus, OH, USA: Amer. Soc. Nondestruct. Test., 1987.

[120] D. Petersen, R. Link, P. Chen, P. Chua, and G. Lim, “An experimental study of monitoring internal leakage in water hydraulic cylinders using acoustic emission,” *J. Test. Eval.*, vol. 33, pp. 445–451, 2005, doi: 10.1520/jte12534.

[121] V. V Shanbhag, T. J. J. Meyer, L. W. Caspers, and R. Schlanbusch, “Diagnostics of seal and rod degradation in hydraulic cylinders using acoustic emissions,” in *Proc. Eur. Conf. PHM Soc.*, 2020, pp. 1–8. [Online]. Available: http://www.phmpapers.org/index.php/phme/article/view/1173

[122] V. V. Shanbhag, T. J. J. J. Meyer, L. W. Caspers, and R. Schlanbusch, “Condition monitoring of hydraulic cylinder seals using acoustic emissions,” *Int. J. Adv. Manuf. Technol.*, vol. 109, pp. 1–13, 2020, doi: 10.1007/s00170-020-05738-4.

[123] M. Ramachandran and Z. Siddique, “A data-driven, statistical feature-based, neural network method for rotary seal prognostics,” *ASME J. Nondestruct. Eval.*, vol. 2, 2019, Art. no. 024501, doi: 10.1115/1.4043191.

[124] M. Ramachandran and Z. Siddique, “Statistical time domain feature based approach to assess the performance degradation of rotary seals,” in *Proc. Int. Mech. Eng. Congr. Expo.*, 2018, Paper V013T05A071, doi: 10.1115/IMECE2018-87857.

[125] M. Ramachandran, J. Keegan, and Z. Siddique, “A hybrid PSO-SVM based method for degradation process prediction of reciprocating seal,” in *Proc. Annu. Conf. PHM Soc.*, 2019, pp. 1–9, doi: 10.36001/phmconf.2019.v11i1.852.

[126] N. Helwig, E. Pignanelli, and A. Schutze, “Condition monitoring of a complex hydraulic system using multivariate statistics,” in *Proc. Int. Instrum. Meas. Technol. Conf.*, 2015, pp. 210–215, doi: 10.1109/I2MTC.2015.7151267.

[127] S. S. Chawathe, “Condition monitoring of hydraulic systems by classifying sensor data streams,” in *Proc. IEEE 9th Annu. Comput. Commun. Workshop Conf.*, 2019, pp. 898–904.

[128] H. Murrenhoff, “Environmentally friendly fluids—Chemical modifications, characteristics and condition monitoring,” *O+ P Ölhydraulic und Pneum.*, vol. 48, no. 3, pp. 141–161, 2004.

[129] D. Lovrec and V. Tič, “On-line condition monitoring systems for hydraulic machines,” *Facta Univ. Mech. Eng.*, vol. 10, no. 1, pp. 81–89, 2012.

[130] HYDAC, “Fluid monitoring module,” Accessed: Jun. 4, 2020. [Online]. Available: https://www.hydac.com/de-en/products/measurement-display-and-analysis-tools/measuring-instruments/contamination-measurement-devices/fmm.html

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