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Review

A Critical Review of On-Line Oil Wear Debris Particle Detection Sensors

Wenbo Han, Xiaotong Mu, Yu Liu, Xin Wang, Wei Li, Chenzhao Bai and Hongpeng Zhang *

Marine Engineering College, Dalian Maritime University, Dalian 116026, China; wenbo_han@126.com (W.H.); 13224845070@163.com (X.M.); liuyu0717@dlmu.edu.cn (Y.L.); dmuwangxin@dlmu.edu.cn (X.W.); dmuliwei@dlmu.edu.cn (W.L.); baichenz@163.com (C.B.)
* Correspondence: zhppeter@dlmu.edu.cn

Abstract: In the field of marine engineering, the friction and wear experienced by rotating mechanisms are recognized as significant contributors to the failure of marine machinery. In order to enhance the safety and dependability of marine ship operations, the implementation of on-line oil wear debris particle detection sensors enables the on-line monitoring of oil and facilitates the rapid identification of abnormal wear locations. This paper provides a critical review of the recent research progress and development trends in the field of sensors for on-line detection of oil wear debris particles. According to the method of sensor detection, wear debris particle detection sensors can be classified into two distinct categories: electrical and non-electrical sensors. Electrical sensors encompass a range of types, including inductive, capacitive, and resistive sensors. Non-electrical sensors encompass a range of technologies, such as image processing sensors, optical sensors, and ultrasonic sensors. Finally, this review addresses the future research directions for wear debris particle detection sensors in light of the challenging problems currently faced by these sensors.

Keywords: wear debris particle detection sensor; on-line oil detection; marine engineering; electrical; non-electrical

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1. Introduction

The optimal functioning of marine engineering machinery and equipment plays a crucial role in ensuring the safety and efficiency of ships during their operations at sea [1]. In recent years, the rapid advancement and proliferation of smart ship and unmanned ship technology has generated a pressing demand for on-line monitoring and early warning systems to assess the operational condition of marine engineering machinery and equipment [2]. In the field of marine engineering, the occurrence of component wear and failure is a prevalent form of failure. It is of utmost importance to closely monitor the wear condition of marine engineering machinery and equipment [3]. Lubricating oil is commonly recognized as the vital fluid that enables the smooth functioning of mechanical equipment [4,5]. The oil in mechanical equipment serves multiple purposes, including power transmission, lubrication, and cooling. Additionally, the presence of metal particles in the oil provides valuable information regarding the friction and wear of the equipment [6].

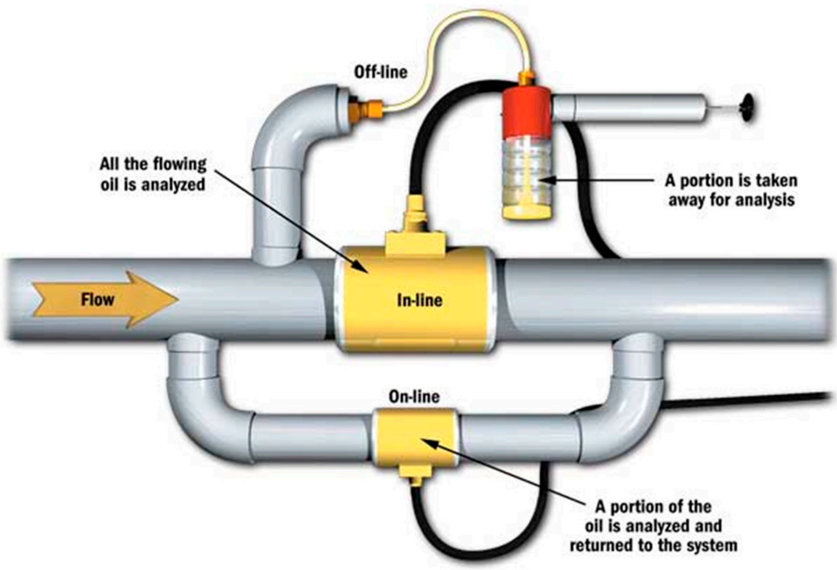
Marine engineering machinery and equipment typically consist of ferromagnetic, paramagnetic, and diamagnetic materials [7,8]. The friction and wear process of mechanical equipment is a multifaceted and dynamic phenomenon that can be divided into three distinct stages: the running-in period, the stable wear period, and the severe wear period [9,10]. Different stages of friction and wear result in the generation of metal particles that possess distinct characteristic information, exhibiting variations in size, shape, and concentration [11]. When abnormal wear takes place, it disrupts the equilibrium state of metal particles present in the oil. Consequently, there is an increase in particle concentration, with the particle size typically ranging between 50 and 100 μm [12,13]. When the size of metal particles falls within the range of 150–350 μm, it typically signifies the presence of wear-induced failure [14]. According to the causes of wear failure and wear mechanisms, various types of wear can be identified, including adhesive wear, abrasive wear, fatigue wear, and corrosive wear [15]. Different types of wear result in the generation of distinct forms of metal particles, namely spherical particles, cutting particles, flake particles, fatigue-induced particles, and particles caused by severe sliding [16]. The phenomenon of friction and wear in mechanical equipment is a multifaceted and intricate process of evolution. The size of particles, magnetic characteristics, and concentration of wear debris particles present in the oil can serve as indicators of the friction and wear experienced by marine engineering machinery and equipment [17]. In the context of marine engineering machinery and equipment, the assessment of metal particle size in the oil can provide valuable insights into the friction, wear rate, and overall condition of such machinery and equipment. By effectively distinguishing between ferromagnetic metal particles and non-ferromagnetic metal particles present in oil, it is possible to accurately identify the worn parts of marine engineering machinery and equipment [18].

Therefore, the utilization of oil wear particle detection sensors holds significant importance in the field of marine engineering. The detection methods for oil wear debris particles primarily consist of off-line detection and on-line detection. The specific detection locations of these sensors are shown in Figure 1a. Off-line testing mainly refers to taking the oil out of the circuit and sending it to the laboratory for oil sample testing and analysis. Although the off-line detection method has high detection accuracy, it has many sampling procedures and complex laboratory operations and is inefficient, making it difficult to reflect the actual health status of marine engineering machinery and equipment in a timely manner. Compared with off-line detection methods, on-line detection of oil does not require complex instruments and equipment and professionals. On-line detection of oil can promptly reflect potential mechanical failures and meet the needs of the intelligent and unmanned development trend of marine engineering machinery and equipment. Certainly, based on the underlying detection principles, on-line oil wear debris detection sensors, as illustrated in Figure 1 and Table 1, can be broadly categorized into two primary types: electrical and non-electrical sensors [19,20]. These sensors play a vital role in assessing the condition of machinery by identifying the presence of wear particles in oil [21,22]. Electrical on-line oil wear debris detection sensors mainly include three typical sensors: inductive, capacitive, and resistive [23]. Non-electrical on-line oil wear debris detection sensors mainly include image processing, optical, and ultrasonic sensors [24–26]. In marine engineering, selecting the appropriate type of on-line oil wear debris detection sensor depends on factors such as the type of machinery, the specific wear particles of concern, and the desired sensitivity and accuracy [27,28]. These sensors play a crucial role in monitoring the condition of ship mechanical systems and facilitating timely maintenance to ensure safe and efficient operation at sea [29]. The on-line oil wear debris detection sensor holds significant application value in marine ship equipment wear detection [30]. These sensors can identify wear particles in on-line or at regular intervals, enabling early detection of equipment wear and tear [31]. This early warning allows for proactive maintenance, reducing the risk of unexpected breakdowns at sea [32]. By detecting wear in its incipient stages, these sensors help prevent costly and potentially catastrophic failures of critical ship equipment, ensuring the safety of the vessel and its crew [33]. These sensors provide data and insights into wear patterns, allowing for data-driven decision-making regarding maintenance schedules, component replacements, and system upgrades [34]. Timely detection and maintenance can prolong the lifespan of ship equipment, reducing the need for costly replacements and improving the overall efficiency of the vessel [35,36]. In summary, on-line oil wear debris detection sensors are instrumental in marine engineering for their ability to enhance safety, reduce operational costs, prolong equipment lifespan, and support environmentally responsible practices by efficiently monitoring and managing wear in ship equipment [37,38].

This review aims to examine the recent research progress and development trends in on-line oil wear debris detection sensors, specifically their applications in monitoring the wear state of marine ship equipment. In this review, the wear particle detection sensor is examined based on the principle of detecting wear debris. The review focuses on two categories of sensors: electrical and non-electrical sensors. Finally, this study provides a summary and highlights the potential future research and development directions for an on-line oil wear debris sensor that can be effectively utilized in monitoring the wear condition of marine ship equipment.

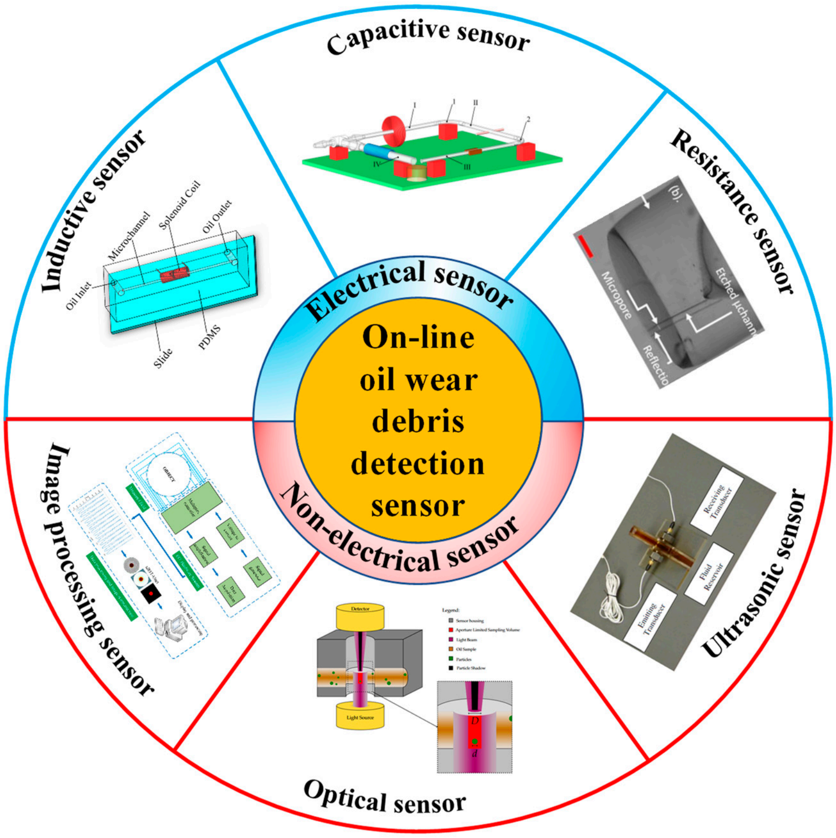
Table 1. Summary of on-line oil wear debris detection sensors used in marine engineering.

Detection Type	Sensor Type	Distinguish Ferrous and Non-Ferrous Particles	Advantages	Disadvantages	References
Electrical sensors	Inductive sensor	Yes	Simple structure, easy to implement on-line, distinguish ferromagnetic and non-ferromagnetic metal particles	Unable to differentiate between non-metallic particles	[39–66]
	Capacitive sensor	No	Simple structure and high sensitivity	Unable to distinguish metal particle properties	[67–78]
	Resistance sensor	No	Detection of particle concentration and size distribution	Poor accuracy, high accuracy only for oil containing a large amount of metal particles	[79–81]
Non-electrical sensors	Image processing sensor	No	The particle morphology can be directly observed to infer the particle composition with high sensitivity	Equipment is expensive and testing process is slow	[82–91]
	Optical sensor	No	High sensitivity, fast detection speed, and particle morphology analysis	High cost, easily affected by oil discoloration and particle aggregation and unable to distinguish particle properties	[92–96]
	Ultrasonic sensor	No	Unaffected by oil discoloration, solid particles and bubbles can be distinguished	Lower sensitivity and greater vibration impact	[97–100]



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. (**a**) Oil particle analysis monitoring location [16] (**b**) Classification diagram corresponding to the on-line oil wear debris detection sensor employed for monitoring the wear state of marine equipment [43,72,79,85,92,100].

2. Electrical Wear Debris Detection Sensors

2.1. Inductive Sensor

Inductive sensors function based on electromagnetic principles. They detect wear particles in the oil by monitoring alterations in electromagnetic properties as the particles traverse a magnetic field. Inductive sensors demonstrate a high level of efficacy in detecting wear particles that are ferrous in nature, primarily composed of iron. Inductive sensors, however, have a limitation in that they can only detect ferromagnetic materials, and furthermore, these materials must possess good conductivity. In 2018, Sanga et al. introduced a novel microcontroller-based inductive quasi-digital sensor that gained recognition for its cost-effectiveness, low power consumption, and remarkable precision in detecting metallic wear particles present in lubricants utilized in rotating machinery [39]. These sensors enabled continuous on-line monitoring of lubricating oils and featured an LCD display that would trigger an automatic alarm when metal particles exceeding 50 μm were detected, indicating a potentially dangerous machine state. Experimental studies have demonstrated the sensor's efficacy in accurately detecting and monitoring iron particles as small as 30 μm, as well as non-ferrous metal particles with a diameter of 70 μm. In 2012, Du et al. successfully implemented an inductive wear particle detection sensor with seven parallel microchannels, enabling efficient high-throughput on-line monitoring of lubricant oil. This achievement was made possible by leveraging the Coulter counting principle [40]. The sensor design implemented in their study involved the integration of two layers of planar coils and microchannels. Experimental investigations highlight the impressive capability of the sensor to effectively process two milliliters of lubricating oil per minute, while simultaneously ensuring minimal interference between the seven microchannels. In contrast to single-channel systems, the utilization of a multi-channel monitoring approach has been shown to be an exceptionally effective strategy for achieving high-throughput detection. In 2017, Zhu et al. introduced a portable inductive wear debris sensor with a ferrite core as part of the ongoing efforts in the field of on-line machine health monitoring [41]. The sensor described possesses the ability to detect iron particles with diameters of 11 µm and 50 µm. This is achieved through the measurement of inductance using two planar coils that are wound around a pair of ferrite cores. The design of their sensors enables the attainment of a magnetic flux that is characterized by higher density, greater uniformity, and enhanced sensitivity in comparison to previous models. The results of the study revealed the successful achievement of high-throughput on-line monitoring, with a sampling rate of 750 milliliters per minute, using the simultaneous sampling technique. It has been demonstrated to be particularly well-suited for the on-line monitoring of wear particles of smaller sizes. Zhu et al. developed a 3×3 time-division multiplexed inductive sensor specifically designed for efficient high-throughput particle monitoring in 2017 [42]. The sensor employed in this study effectively addresses crosstalk issues by employing a hybrid approach that combines time division multiplexing and series diodes. This approach enables the attainment of sequential responses within each channel. The study findings emphasize the sensor's ability to accurately monitor wear particles as small as 50 µm. The utilization of the simultaneous sampling approach in the study led to a substantial decrease in the time required for data processing. This novel design concept has the potential to be extended in order to establish an $N \times N$ sensor array mode, which would enable efficient monitoring of lubricant wear particles with high throughput. In 2020, Bai et al. developed a novel dual solenoid inductive sensor for the detection of magnetic nanoparticles. This sensor demonstrated enhanced detection accuracy in comparison to conventional single solenoid sensors, as depicted in Figure 2 [43]. Through the utilization of theoretical analysis and scanning electron microscopy, the researchers were able to identify the optimal concentration of nanoparticles and subsequently confirm that the sensitivity of this sensor in detecting magnetic nanoparticles was significantly enhanced, exhibiting a notable increase of 19–24%. Hong et al. introduced a novel hybrid detection strategy that employs a generic calibration framework based on artificial neural networks in 2020 [44]. This approach effectively reduces detection errors under different mixing conditions in inductive abrasive particle sensors. The findings of their study showcased the efficacy of the proposed scheme, as it achieved results with an error rate of less than 20% across a range of abrasive particle concentrations, from 5 mg/L to 100 mg/L. One limitation of this approach is the requirement for network redesign and retraining when implementing it with different inductive sensors or under varying operational conditions. Xiao et al. conducted a research study on an inductive sensor that was specifically designed for the purpose of detecting metal abrasive particles in large-diameter pipes in 2019 [45]. Experimental results demonstrated that the output signal obtained from the sensor in the lubricating oil circuit, which relied on a high-gradient magnetic field, displayed a linear relationship with the driving current. The sensor, however, had a limited capability in detecting debris that had a z-axis height smaller than the diameter of the pipes. Notably, the effectiveness of detection was impacted when the axial separation between two abrasive particles fell below 25 mm, leading to aliasing in the induced voltage signals of the two particles. Ren et al. developed an inductive abrasive particle sensor that incorporates multiple induction coils strategically placed around an excitation coil in 2018 [46]. Diverging from conventional sensor configurations, this particular design utilizes the simultaneous operation of multiple coils to effectively facilitate the coupling of the excitation magnetic field with the sensing end. This approach serves to increase the output voltage and improve sensitivity. Empirical evidence substantiates the sensor's ability to precisely quantify iron particles with a diameter of 120 µm and non-ferrous metal particles measuring 210 µm in diameter. The novel methodology for sensor design effectively reduces the monitoring limit for inductive abrasive sensors.

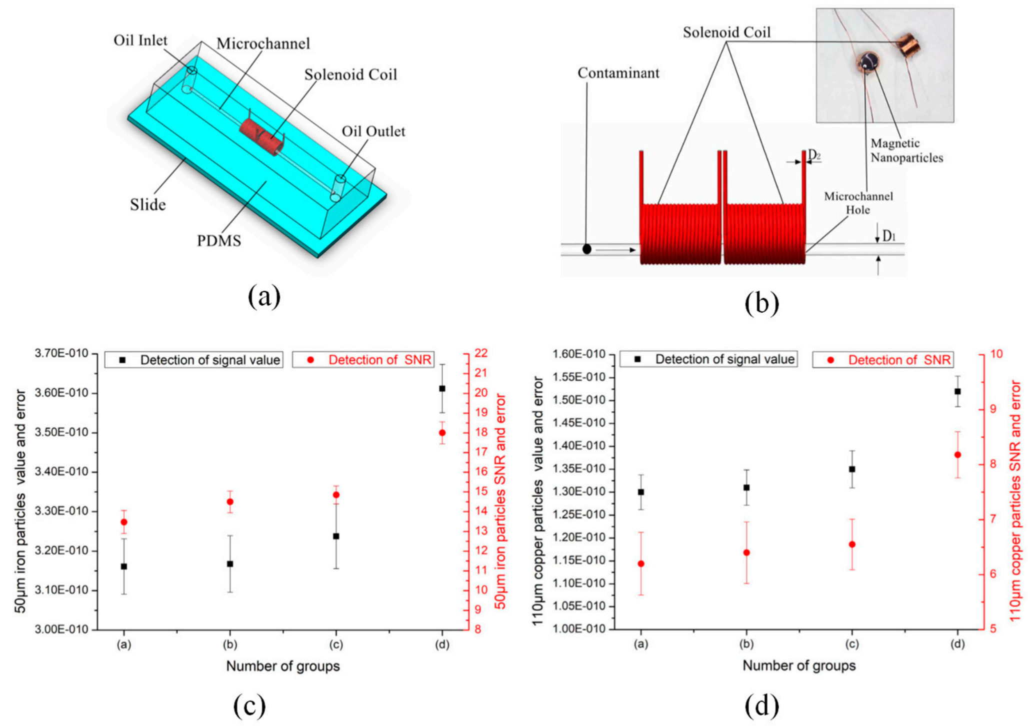


Figure 2. Inductive wear particle detection sensor based on PDMS [43]. (**a**) Structural design of inductive sensor. (**b**) Schematic diagram of wear particles passing through the sensor. (**c**) The detection results of iron particles with a diameter of 50 μm in the inductive detection sensor. (**d**) The detection results of copper particles with a diameter of 100 μm in the inductance detection sensor.

In 2020, Zeng et al. introduced a highly sophisticated micro-impedance sensor that incorporates two solenoid coils and eight silicon steel needles. This sensor is designed for the purpose of monitoring the condition of oil [47]. The inclusion of silicon steel needles serves to enhance the concentration of the magnetic field in the sensor, thereby leading to an enhancement in the intensity of magnetic induction. Research findings indicate that the sensor has the ability to accurately detect iron particles with a diameter of 18 μm and copper particles measuring 75 μm when operating in the inductive mode. Notably, the micro-impedance sensor presented in this study features a simple design and does not necessitate the use of intricate external circuits. When utilized for high-throughput wear particle detection, the sensor is susceptible to producing aliasing signals as wear particles traverse it. This has the potential to affect the evaluation of wear particle concentration and size. In 2021, Muthuvel et al. initiated the development of an innovative inductive sensor that employs a passive wireless LC sensing method. This sensor is specifically designed for monitoring wear particles in high-pressure hydraulic circuits [48]. The external coil of the sensor is energized by an alternating current (AC) signal that operates at the balanced resonant frequency of the system. As a result of wear particles passing through it, the sensor experiences a phase shift in its response. By conducting an analysis of the fluctuating direction of the output phase, this sensor demonstrates the capability to accurately differentiate between ferrous and non-ferrous metals that are present within the oil. The findings of their study demonstrated that the sensor possesses the ability to detect metal particles with a size exceeding 25 μm, while maintaining a flow rate of 40 L/min. In 2020, Wang et al. conducted a study to gain insights into the phenomenon of signal aliasing [49]. The investigation focused on examining the effects of various factors, including wear particle motion state, motion speed, spatial position, and others, on the waveform of aliasing signals within inductive sensors. A direct relationship has been discovered between the voltage induced by aliasing and the velocity of wear particles. Furthermore, the peak-to-peak voltage of the aliasing signal is also found to be proportional to the radius of the wear particles. In 2020, Li et al. conducted a comprehensive investigation on a novel inductive wear particle monitoring sensor. The sensor showcased a distinctive design, characterized by a three-coil inverted dual-excitation solenoid [50]. Using the Time Harmonic Electromagnetic Field Analysis (THEFA) method, the researchers performed finite element numerical simulations to investigate the impedance and coil characteristics of the sensor. They then conducted experimental tests to validate their theoretical findings. Their research findings revealed that the sensitivity of the sensor could be greatly improved by employing a meticulous design strategy that takes into account various factors such as the height, thickness, distance, and turn density of both the excitation and induction coils. To achieve accurate voltage output signals, a pass-band filter amplifier circuit was developed with the objective of eliminating harmonics in the output voltage signal. This approach enables high-resolution and high-sensitivity measurements of wear particles. In 2019, Feng et al. conducted a thorough investigation on an inductive wear particle sensor that utilizes a high-gradient magnetic field [51]. They have developed a mathematical model to investigate the theoretical relationship between the induced voltage and the size of wear particles that are produced when they traverse through the high-gradient magnetic field of the sensor. The experimental findings have substantiated the sensor's efficacy in detecting ferromagnetic wear particles with a minimum diameter of 25 μm. Qian et al. conducted groundbreaking research in 2021, being the first to theoretically investigate and provide empirical evidence that the residual voltage, arising from the asymmetry of two excitation coils, is a crucial factor that constrains the potential improvement in resolution of inductive debris sensors [52]. To attain automated suppression of residual voltage, the researchers developed a three-coil inductive abrasive particle sensor that incorporates a two-stage self-asymmetric compensation circuit. Experimental results demonstrated that the sensitivity of the sensor surpassed that of a sensor lacking this compensation by a factor of more than 31. This enabled successful detection of iron abrasive particles with a diameter of 70 μm and non-ferrous abrasive particles measuring 165 μm in diameter. This experiment highlighted the notable benefits of employing the automatic asymmetric compensation circuit (AACC), specifically in attaining exceptionally high levels of resolution and sensitivity in the sensor. Wu et al. introduced a novel inductive wear particle detection sensor that incorporates dual excitation and dual induction coils in 2021 [53]. Through rigorous experimental validation, the researchers have conclusively demonstrated that the sensor exhibits exceptional sensitivity, enabling it to accurately detect ferrous metal particles measuring 115 μm and non-ferrous metal particles measuring 313 μm in size. Additionally, the study conducted by the researchers aimed to investigate the influence of variables such as excitation frequency and radial distribution of the magnetic field on the sensitivity of the inductive sensor. In their pursuit of improving the accuracy of wear level monitoring in ferromagnetic rigid friction pairs, Feng et al. developed an innovative inductive sensor that is specifically tailored for monitoring ferromagnetic particles. This sensor utilizes a high-gradient static magnetic field in 2021 [54]. The sensor configuration consists of two cylindrical magnetic rings and a magnetic housing. By employing a mathematical model and employing finite element analysis, the researchers were able to acquire the magnetic field distribution and output voltage waveform of the sensor. The numerical simulation results provided clarification on the influence of induction coil length, coil position, and particle radial position on the output voltage. Ultimately, the research findings demonstrated the sensor's efficacy in detecting ferromagnetic particles, even at high flow rates, with a minimum diameter of 13 μm. Park et al. developed an inductive metal particle detection sensor through the utilization of an aerosol-hydrosol adoption method in 2021 [55]. The aforementioned sensor is capable of converting measurement signals into the concentration of ferrous metal particles, thereby exhibiting its capacity to differentiate between ferrous and non-ferrous metals. Research findings suggest that the sensor demonstrates a high level of effectiveness in detecting iron particles within the size range of 5 to 10 μm, as well as copper particles sized between 50 and 60 μm. Comparatively, the sensor demonstrates a commendable level of consistency when compared to high-precision commercial measuring instruments. This characteristic renders it suitable for the detection of small-size metal particles. However, its effectiveness diminishes when it comes to detecting larger-size metal particles. Wu et al. presented a novel methodology for quantifying the dimensions of non-ferrous metal particles by utilizing the impedance signal generated by an inductive sensor coil in 2021 [56]. In contrast to traditional investigations on inductive sensors, their approach solely concentrated on analyzing the imaginary component of the coil impedance signal output. Theoretical analysis has demonstrated that the coil impedance encompasses both real and imaginary components, which can be described by an elliptic function in the presence of coupled signals originating from various materials. Through conducting measurement experiments on aluminum and copper particles, the researchers were able to demonstrate that the sensor's measurement results showed an error rate of less than 12.8% when compared to the results obtained through optical microscope measurement. In scenarios where the accurate identification of material and size of multiple mixed metal wear particles is challenging using conventional inductive mixers, Li et al. proposed a solution in 2022, as depicted in Figure 3 [57]. A triple-coil inductive sensor, integrated with a double lock-in amplifier circuit (DLAC), was utilized to detect complex-domain signals emitted by metal particles, even in the presence of noise interference. The experiments conducted on the detection of five different metal particles using complex-domain signal detection showed that the inductive sensor based on DLAC demonstrated exceptional precision, resolution, noise immunity, and minimal zero drift. These findings effectively address the identified issues.

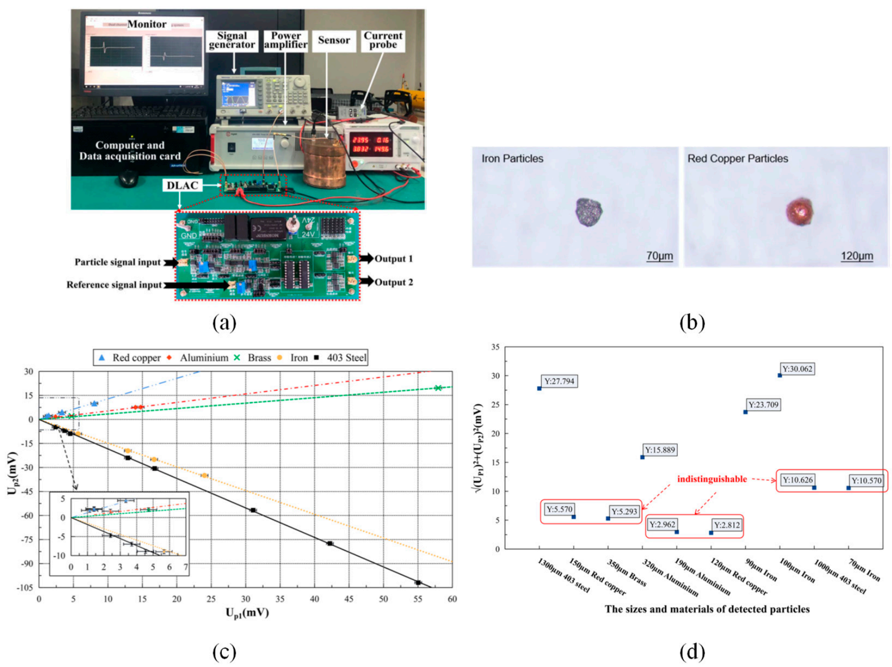


Figure 3. Inductive wear particle detection sensor based on dual lock-in amplifier circuit [57]. (**a**) Experimental system components for particle detection. (**b**) Microscopic images of iron particles with a diameter of 70 μm and copper particles with a diameter of 120 μm. (**c**) Complex plane distribution plot of particles of different sizes and materials. (**d**) The detection results obtained by real domain detection.

In 2021, Bai et al. conducted an investigation on a wear particle monitoring sensor that utilized a toroidal magnetic field and pairs of induction coils to evaluate the induced voltage in said coils [58]. By incorporating an annular magnetic field into the induction coil, the researchers were able to minimize the influence of abrasive particle trajectories, thereby improving the accuracy of monitoring and successfully attaining the objective of high-throughput and high-precision monitoring. The conducted experiments, encompassing single-particle monitoring and dynamic lubricating oil monitoring, unveiled negligible crosstalk signals that were overshadowed by noise. Overall, the experimental results presented in this study illustrate the sensor's effectiveness in conducting real-time monitoring of 13 μm iron particles at a flow rate of 570 mL/min. To improve the sensitivity of inductive sensors, Yu et al. introduced a signal decomposition technique utilizing Symplectic Geometric Mode Decomposition (SGMD) in order to extract distinctive wear particle signals in 2021 [59]. The SGMD decomposition method was compared with the Empirical Mode Decomposition (EMD) and wavelet decomposition methods in order to analyze simulated abrasive particle signals. The findings demonstrated that the SGMD decomposition method proposed by the researchers exhibited superior performance compared to other methods in the context of on-line monitoring of abrasive particles in lubricating oil. Although the SGMD decomposition method has proven to be effective in enhancing the sensitivity of the inductive abrasive sensor, there remain unresolved challenges pertaining to the calculation speed and end effects associated with this method. Xie et al. conducted an investigation on a bridge-type inductive wear particle detection sensor that incorporates a secondary filter circuit in 2021 [60]. The sensor configuration comprises a dual solenoid coil, a Wheatstone bridge structure sensing unit, and a secondary filter circuit. By implementing circuitry control techniques such as rectification, amplitude modulation, and amplification, the researchers successfully mitigated the impact of environmental and external system noise interference, thereby significantly improving the accuracy of the sensor's detection capabilities. The bridge inductive sensor demonstrated a reliable capability to detect iron particles with a diameter of 45 μm. Huang et al. conducted a comprehensive investigation into the detection characteristics of abrasive particles in inductive abrasive particle sensors in 2022 [24]. A mathematical model was developed to analyze the change in inductance through theoretical analysis and numerical simulations. The study aimed to investigate the impact of various parameters, such as the physical properties of metal abrasive particles, on the induced electromotive force. The research findings presented in this study highlight the successful detection capabilities of the sensor in identifying metal particles. Specifically, the sensor was able to detect ferromagnetic abrasive grains larger than 100 μm and non-ferromagnetic abrasive grains larger than 200 μm. However, the current sensor does not possess the capability to detect abrasive grains of smaller sizes. Hu et al. developed an inductive sensor that incorporates dual excitation and a multi-induction structure, specifically designed for efficient monitoring of large flow rates, in 2022 [61]. This enhanced sensor design takes advantage of the close proximity between the two excitation elements, allowing for the creation of a strong and balanced gradient magnetic field. The sensor, which is equipped with dual excitation coils and four induction coils, effectively detected iron particles measuring 25 μm. This finding suggests that the dual excitation inductive sensor exhibits both a high flow capacity and exceptional sensitivity. Qian et al. introduced a novel high-sensitivity inductive abrasive particle sensor that incorporates intermittent excitation. This method was specifically designed to expand the detection size range while effectively managing coil heating in 2022 [62]. The intermittent excitation approach employed by the researchers allows for the periodic production of a robust alternating magnetic field within a brief period of time. This technique effectively enhances the sensitivity of the sensor and reduces the heating of the coil. The findings of the study revealed that the sensor demonstrated successful detection of iron particles within the size range of 48 to 1426 μm, as well as copper particles measuring between 112 and 3802 μm. This sensor presents significant benefits in terms of broadening the spectrum of detectable particle sizes and reducing coil heating, albeit requiring externally applied intermittent current excitation. Additionally, the reliability and availability of abrasive sensors can be constrained by the presence of noise and other contaminants commonly associated with mechanical wear. In 2023, Shen et al. developed a novel inductive wear particle sensor with a four-coil structure. Shen then conducted a comprehensive analysis using numerical simulations to investigate the factors that influence sensor sensitivity and output [63]. By employing the coherent demodulation technique, the researchers were able to effectively recover the simulated signal from the sensor signal. This experiment confirmed that the four-coil sensor has the capability to determine both the material and size of particles by analyzing the amplitude and phase of the signal. A comparative assessment was conducted to evaluate the detection capability of ferromagnetic particles and copper particles. The results revealed that the four-coil sensor demonstrated the highest detection capability for ferromagnetic particles. Luo et al. developed a wear particle monitoring sensor with parallel dual coils using an inductive approach in 2023 [64]. They proposed an adaptive weighted filtering technique with the objective of efficiently attenuating noise. The authors also performed theoretical analysis to evaluate the method's viability, supported by numerical simulations. The validity of this theoretical framework was subsequently confirmed through experiments conducted to verify petroleum. This framework presents significant benefits in terms of harmonics elimination, noise suppression, and preservation of the unique attributes of wear particles. Given the potential for overlapping induced voltages from multiple wear particles passing through the sensor, there is a risk of erroneous peak value evaluations of the resulting waveform. To address this issue, Chen et al. proposed the use of an inductive sensor integrated with a fully convolutional neural network (FCNN) that is capable of effectively separating these aliased signals in 2022 [65]. The feasibility and stability of the sensor were verified through the utilization of finite element numerical simulations and experiments. The research conducted by the authors showcased the significant advantages of the FCNN-based method. It effectively reduced the average error rate by more than 10% and the maximum error rate by over 40% through signal separation. However, it is crucial to acknowledge that this approach may lead to imprecise estimations of particle volume. Therefore, it is imperative to integrate it with particle identification methods that rely on image processing to achieve more precise particle evaluation. Li et al. utilized an asymmetric dual-coil magnetic excitation balanced magnetic field inductive sensor to perform real-time monitoring of metal wear particles in mechanical transmission systems in 2022 [66]. This sensor design incorporates an asymmetric double-coil magnetic excitation, which effectively mitigates the influence of the primary magnetic field on the response magnetic field of metal wear debris. The design also incorporates a balanced magnetic field distribution model, ensuring accurate detection and measurement of metal wear debris. Through the implementation of oil circuit experiments conducted in flow channels with a significant diameter, which were filled with metal particles, the findings of the study showcased the sensor's remarkable capability in effectively monitoring particles that are ferromagnetic and as small as 100 μm, as well as non-ferromagnetic particles that measure up to 1000 μm. Furthermore, the sensor successfully accomplished the objective of swiftly detecting impurities in hydraulic oil. Wang et al. developed an inductive wear particle detection sensor that employs the high-frequency voltage synchronous sampling technique in 2022 [8]. This sensor is specifically designed to detect ferromagnetic particles that are flowing rapidly, while ensuring that the signal amplitude remains unaffected. This novel approach effectively reduces the influence of wear particle flow velocity on the detection signal, thereby facilitating precise measurement of high-speed particle flow. However, the utilization of the high-frequency voltage sampling method necessitates more advanced sampling equipment and enhanced signal output stability, leading to increased detection expenses and a more intricate detection procedure. Furthermore, the present capabilities of this sensor are restricted to the detection of ferromagnetic particles, and its effectiveness in detecting non-ferromagnetic particles is still uncertain.

2.2. Capacitive Sensor

Capacitive sensors operate by detecting changes in capacitance caused by the movement of wear particles within an electric field. They depend on variations in the dielectric characteristics of the oil caused by the existence of particles. Capacitive sensors have the capability to detect particles, regardless of whether they are metallic or non-metallic. In 2005, Raadnui et al. developed a cost-effective capacitive sensor specifically designed for the purpose of monitoring suspended wear metal particles and contaminants present in lubricating oils [67]. The sensor is characterized by a grid of sensing elements that are arranged in parallel with multiple small gaps between them. It has been demonstrated that the presence of contaminants, specifically iron particles, has a significant influence on the observed variations in lubricant degradation as detected by the sensor. In the field of aero-engine health monitoring, the on-line monitoring of wear particles in lubricating oil is of utmost importance. Han et al. proposed the use of a cylindrical capacitive sensor that consists of two coaxial cylinders in 2017 [68]. They successfully incorporated this sensor into the piping of an aero-engine lubrication system in order to monitor changes in the conditions of the lubricating oil. Their methodology encompassed the establishment of mathematical models and the execution of numerical simulations in order to analyze the sensing mechanism and characteristics of capacitive sensors. Experimental validation has shown that capacitance values can be used to characterize wear particles. Additionally, compensation methods have been proposed to improve the accuracy of the sensor. Leveraging microfluidic technology, Bai et al. demonstrated the versatility of a capacitive sensor specifically designed for high-throughput hydraulic oil detection in 2019 [69]. This sensor is capable of seamlessly transitioning from capacitive to inductive working mode. This particular sensor is equipped with a set of silicon steel sheets that possess an annular microchannel. This unique feature allows for the manipulation of the magnetic field within the silicon steel sheet by modifying the connection of the coil. Consequently, the sensor enables the identification and categorization of diverse pollutants with exceptional flexibility. Liu et al. introduced a capacitive sensing system that was specifically developed to evaluate the level of wear in marine diesel engines in 2000 [70]. This system functions by detecting changes in the dielectric constant of the lubricating oil in order to assess its quality. The lubricating oil quality detector, consisting of upper and lower capacitors, is capable of accurately detecting real-time changes in oil quality caused by contaminants such as water and metal wear particles. Wang et al. proposed a novel capacitive sensor network system aimed at detecting wear particles in lubricants used in aero-engines in 2022 [71]. This system incorporates parallel curved electrodes and non-parallel planar electrodes, resulting in the formation of multiple subspaces characterized by decreased electrode distances. Each subspace comprises two distinct pairs of electrodes. As wear particles traverse these spaces, alterations occur in the dielectric constant between the electrodes and the capacitance existing between them. Experimental findings suggest that there is a correlation between the size and mass of wear particles and an increase in the capacitance value of the sensor. In 2020, Islam et al. introduced a novel non-contact cross-capacitive sensor that operates on the Thompson–Lampard principle. This sensor was designed specifically for the detection of abrasive particles in lubricating oil, as depicted in Figure 4 [72]. The sensor, consisting of four cylindrical electrodes, underwent testing using metal particles of varying weights (ranging from 10.5 mg to 27.5 mg) in a lubricating oil. Their research demonstrates that when metal particles traverse the sensor, there is a sudden alteration in the effective dielectric constant of the lubricating oil, resulting in a significant rise in capacitance value. Additionally, the capacitance peak demonstrates variation in accordance with the size of the metal particles, with the largest peak observed at 27.5 mg and the smallest peak observed at 12.2 mg. Additionally, the research findings indicate that the sensor registers capacitive pulses with more distinct peaks and shorter durations when heavier metal particles are in motion at higher velocities. Conversely, lighter particles result in longer pulse durations. The non-contact capacitive sensor described in this study is designed to preserve electrode integrity and achieve a high level of accuracy, with a tolerance of up to $\pm 0.82\%$. Sun et al. developed a microsensor that integrates a 12-plate capacitance array, employing adaptive cytogenetics (SA-CGA) and morphological algorithms, in 2019 [73]. They have also proposed a novel inversion method that utilizes hyper-heuristic partial differential equations to effectively identify multiscale metal abrasive particles. Through conducting finite element simulations of the metal abrasive particle detection system, the researchers investigated the influence of abrasive particle characteristics on plate capacitance. The findings of their study showcased the efficacy of the capacitive array sensor in performing real-time detection of abrasive particles within the range of 200. This was done by comparing the results obtained from the capacitive array sensor with those obtained from an off-line detection CCD imaging system. The measurement is 900 µm. However, one limitation of this sensor is its incapability to detect metal abrasive particles with high throughput. Murali et al. conducted groundbreaking research on a novel capacitive microfluidic sensor that was specifically developed to detect metal abrasive particles in 2009 [74]. This research marked the first utilization of the Coulter counter principle. Recognizing the inherent difficulty in directly measuring alterations in electrical resistance resulting from the presence of abrasive particles, the researchers made the decision to instead monitor fluctuations in capacitance between the two polar plates situated within the microchannel. This experiment showcases the potential utilization of a microfluidic detection apparatus in the domain of identifying abrasive particles in low-conductivity lubricating oil. Zhu et al. utilized a network of coaxial capacitive sensors to evaluate and classify the morphology of metallic wear particles in 2022 [75]. They optimized the parameters of a Support Vector Machine (SVM) model and enhanced its classification accuracy through the implementation of intelligent optimization techniques. This study emphasizes the capability of the coaxial capacitive sensor network to analyze the various dimensions of wear particles. Furthermore, it demonstrates that the optimized Support Vector Machine (SVM) model can accurately classify wear particles present in lubricating oil.

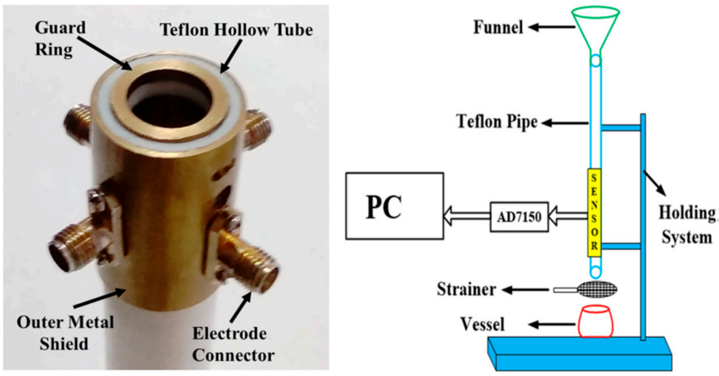


Figure 4. High-precision cross-capacitive metal particle detection sensor [72].

Liu et al. conducted a study on the optimization of parallel resonant circuits in capacitive abrasive sensors. The researchers employed a method that involved adjusting the parallel capacitance to enhance the performance of the sensors in 2022 [34]. The evaluation of the detection quality was conducted through the measurement of the relative impedance change of the LC resonant circuit. The conducted experiments involved the utilization of both ferrous and non-ferrous metal particles and demonstrated a significant level of concurrence between the experimental outcomes and the calculated results. A significant advantage of capacitive devices lies in their ease of replacement in experimental setups, allowing for the adjustment of parallel capacitance as a viable method to optimize abrasive particle sensors in comparison to other types of sensing system devices. In 2022, Wang et al. investigated a high-sensitivity, multi-channel, multi-modal capacitive sensor that was specifically developed for the purpose of detecting wear particles in a high-throughput manner. This sensor is illustrated in Figure 5 [76]. The sensor comprises four glass capillary channels, a planar coil, a solenoid coil, a cylindrical parallel-plate capacitor, and a rectangular parallel-plate capacitor. The system has the capability to achieve high-throughput on-line monitoring of a wide range of pollutants, such as ferromagnetic particles, non-ferromagnetic particles, air, water, and other substances. The detection throughput of the sensor has undergone a substantial improvement, exhibiting a twelve-fold increase compared to its initial value. In 2022, Gao et al. presented a novel capacitive sensor that was specifically developed for real-time monitoring of the mean velocity of metal particle flow in narrow pipes [33]. This sensor employs double triangular electrodes for both numerical simulations and experimental investigations. Importantly, it has been found that the axial position of the metal particles does not have a significant impact on velocity measurements. In the initial experiments, the researchers confirmed the viability of the sensor for measuring the velocity of metal particles, demonstrating a repeatability error of less than 7%. It is important to highlight that the metal particles examined in their study had a relatively large diameter and flow velocity, and the fluid flow was predominantly influenced by gravity. In 2018, Muthuvel et al. conducted a study on an efficient and cost-effective capacitive sensor that was specifically designed for the detection of abrasive particles in hydraulic systems [77]. The methodology entails the utilization of a permanent magnet to attract iron-containing abrasive particles towards the sensor. Subsequently, a capacitive sensor is employed to monitor the presence of iron-containing abrasive particles with a diameter exceeding 200 μm in the lubricating oil. The findings of the research demonstrated that the implementation of the capacitive sensor, employing the differential sensing technique, presented significant benefits such as enhanced sensitivity, cost-effectiveness, and operational efficiency. Additionally, the utilization of permanent magnets effectively attracted ferrous abrasive particles towards the sensor, thereby guaranteeing the absence of any abrasive particles within the hydraulic system's circuit. It is crucial to acknowledge that the current capability of the sensor is limited to monitoring abrasive particles made of ferrous metal. In 2022, Shi et al. presented an innovative integrated multi-unit capacitive sensing microsensor. This microsensor was specifically designed to achieve ultrasensitive detection and comprehensive analysis of various contaminants in oil, including metal wear particles, air bubbles, and moisture [78]. By employing impedance parameters, this sensor exhibits the capability to accurately distinguish between iron filings with sizes ranging from 16 μm to 500 μm, copper filings with sizes ranging from 60 μm to 500 μm, as well as detect air bubbles and moisture in oil that are larger than 170 μm.

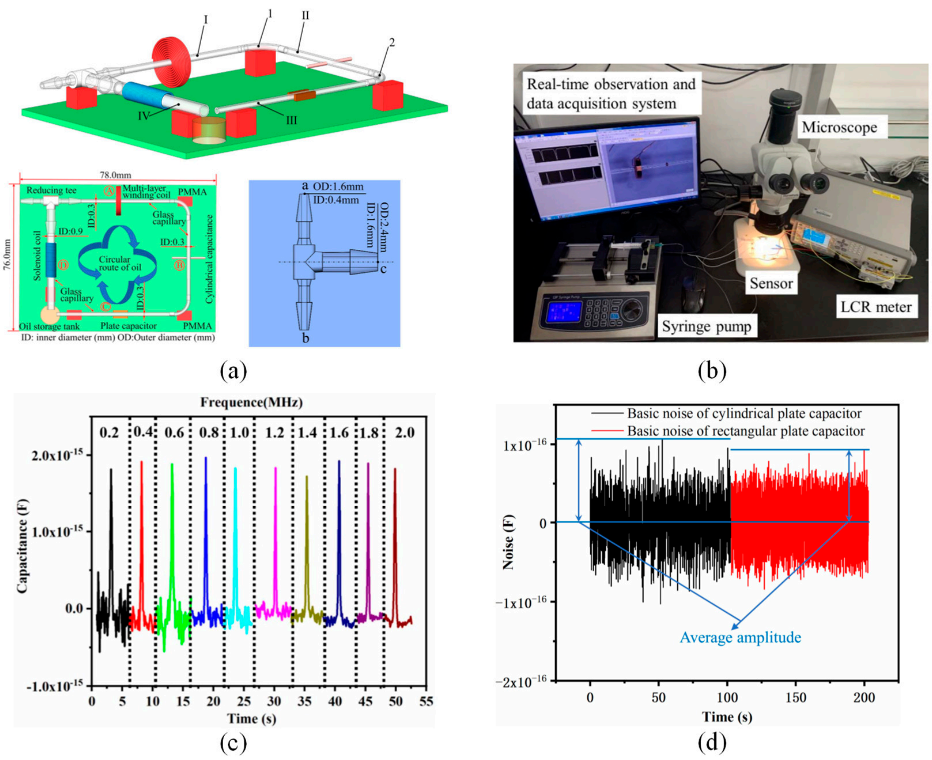


Figure 5. High-sensitivity, high-throughput capacitive detection sensor for oil contamination [76]. (**a**) The overall structure design of the sensor. (**b**) Capacitive sensor experimental test system. (**c**) The detection signals obtained by the cylindrical capacitive sensor under different excitation frequencies. (**d**) Basic noise of different types of capacitive sensors.

2.3. Resistance Sensor

The resistance detection method is employed to identify particulate matter by utilizing the disparity in conductivity among different substances. Resistance sensors are utilized to measure fluctuations in the electrical resistance of the oil. When wear particles are present, they generate conductive pathways that modify the resistance of the oil. These sensors have the capability to detect a diverse array of wear particle types. In 2019, Birkin et al. conducted an experiment to evaluate the performance of a newly developed differential resistive pulse sensor for particle size analysis. The results showed that this sensor had a higher signal-to-noise ratio compared to traditional current sensing techniques, especially when applied to Coulter counting. These findings are illustrated in Figure 6 [79]. The sensitivity of the resistive sensor is contingent upon various factors, including the selection of the resistor and the voltage applied. Song et al. developed a microfluidic-based differential resistive pulse sensor for the purpose of monitoring nanoparticles in 2011 [80]. This sensor is capable of detecting particles through the observation of resistive pulses that are generated when particles pass through a designated sensing region. By implementing differential amplification techniques, the researchers are able to improve the signal-to-noise ratio of the sensor. The aforementioned sensor is highly regarded for its uncomplicated data processing capabilities and exceptional sensitivity. Santilli et al. developed a resistive sensor that is capable of monitoring wear particles by measuring the rate of fluid wear in 1989 [81]. The response of this sensor is influenced by the size and wear properties of both ferromagnetic and non-ferromagnetic particles. The objective is accomplished through the integration of two layers of metal film on its outer surface. When particles in rapid motion collide with the metal film, it undergoes gradual erosion, resulting in an elevation of resistance. Monitoring the change in resistance allows for the identification of wear particles.

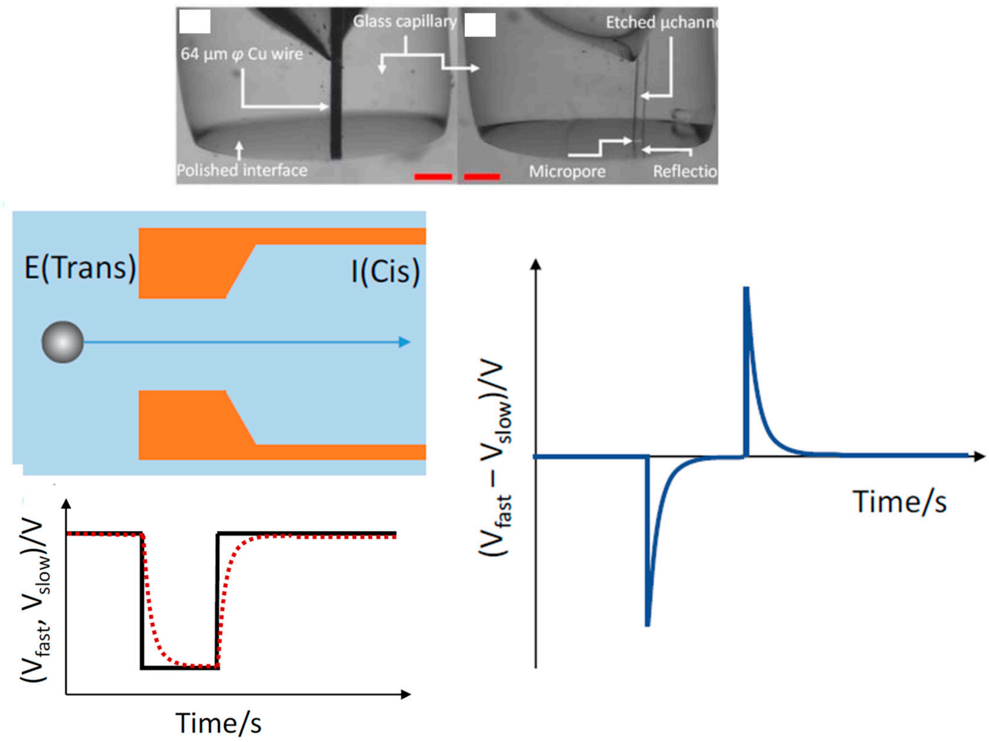


Figure 6. Detection principle of resistive particle detection sensor [79].

3. Non-Electrical Wear Debris Detection Sensors

3.1. Image Processing Sensor

The imaging technique involves capturing images of oil contaminants using CCD or CMOS sensors and extracting information about the types of contaminants and particle morphology through the use of image recognition algorithms. Image processing sensors utilize cameras and sophisticated software to acquire images of the oil sample. The aforementioned images are subsequently subjected to analysis in order to detect the existence of wear particles. This approach exhibits versatility as it is capable of detecting wear particles of diverse nature, while simultaneously offering insights into their dimensions and morphology. Li et al. proposed a novel full-field OLVF wear particle detection sensor that employs reflected light microscopy imaging to improve the precision of on-line wear particle monitoring in 2021 [82]. Through the utilization of Matlab R2023a numerical simulations and subsequent experimental validation, the research conducted by the authors showcased the efficacy and reliability of a newly developed sensor in capturing comprehensive reflection ferrographs of wear debris present in lubricating oil. Furthermore, it demonstrates a higher level of accuracy in extracting indicators of wear particle concentration when compared to conventional OLVF methods. More et al. utilized ferrography as a means to tackle the challenges associated with wear monitoring in conventional gearbox systems in 2021 [83]. By conducting an analysis of wear particles generated in the gearbox and evaluating their characteristics in oil samples collected from the system, the researchers utilized image analysis techniques to distinguish between different types of wear materials based on the color of the wear particles. This approach provides valuable insights into the condition of gearbox systems. Yuan et al. proposed a novel method called the Radial Concave Deviation (RCD) method, which utilizes image processing technology to efficiently identify particle types in 2016 [84] particle boundary signals. They employed image processing techniques to extract RCD parameter values from the boundaries of wear particles, which demonstrated efficacy in differentiating between different wear particle characteristics. It is important to highlight that the detection of OLVF particles using ferrography can present challenges, primarily stemming from the interference caused by reflected light, which can adversely affect the accuracy of detection results. In 2023, Zhu et al. presented a novel algorithm for Electrical Impedance Tomography (EIT) called GN-Unet. This algorithm was specifically developed for imaging the accumulation area of wear particles in lubricating oil. The authors illustrated the algorithm's performance and results in Figure 7 [85]. This method entails the analysis of wear particle characteristics by examining the accumulation area of lubricant wear particles using an algorithm. This algorithm has proven to be highly effective in rapidly and accurately generating images of the wear particle accumulation area. By conducting an analysis of the obtained images, it becomes feasible to evaluate the dimensions and volume of wear particles, thereby facilitating real-time monitoring of the mechanical equipment's overall health condition. Peng et al. presented a pioneering approach in the field of automatic wear particle detection and recognition from raw ferrograph images in 2020 [86]. Their method, named WP-DRnet, is a convolutional neural network that demonstrates significant advancements in this area. This novel neural network demonstrates a high level of efficiency in accurately identifying and segmenting diverse wear particles, regardless of their varying shapes and conditions. In contrast to currently available methods for ferrograph detection and classification, WP-DRnet demonstrates enhanced performance in the identification and classification of wear particles. This approach minimizes the need for manual intervention and reduces processing time. Wang et al. proposed a novel methodology for intelligent ferrography, which addresses the constraints associated with conventional image processing techniques, in 2020 [87]. Their approach, based on Convolutional Neural Networks (CNN), allows for a thorough assessment of wear particle characteristics and the extent of wear. This study presents a CNN-based ferrograph image analysis technique that demonstrates a remarkable average accuracy rate of 90%. This approach provides a rapid and highly accurate processing alternative to traditional methods. Wu et al. proposed a rapid statistical methodology to characterize wear particles by utilizing an on-line ferrograph image sensor in 2011 [88]. The main focus of their research was to analyze wear particle chains rather than individual particles. They have devised two statistical indicators, namely the point-to-point value and the maximum wear debris equivalent diameter, in order to effectively assess the statistical concentration of wear debris and the maximum size of wear debris. The findings suggest that these indicators are efficacious in autonomously delineating the macroscopic and microscopic rates of wear, as well as the mechanisms of wear. Liu et al. developed a microfluidic wear particle monitor with high precision in 2023 [28]. The device integrates a multi-target tracking algorithm, which utilizes numerical simulations and machine vision technology. This monitor not only enables the conventional detection of particle number and size but also facilitates the measurement of particle density and movement speed. Through the utilization of numerical simulations, the researchers conducted an analysis of the distribution of oil flow field and the patterns of particle movement. Experimental findings have provided evidence that the monitor is capable of effectively identifying and measuring the quantity, dimensions, and concentration of wear particles that exceed 20 μm in size and have a density greater than 2000 kg/m^3. Mohanty et al. conducted a study to investigate the correlation between an Artificial Intelligence (AI) model that employs image processing technology and engine parameters for the purpose of fault detection in 2020 [89]. They have presented an innovative Artificial Neural Network (ANN) model that utilizes advanced image processing techniques for the purpose of detecting wear particles and evaluating engine wear characteristics. This study showcases the integration of image analysis with engine condition assessment. Feng et al. proposed an algorithm for wear particle segmentation that effectively tackles the difficulties posed by reflective and light-absorbing regions in 2019 [90]. The methodology employed by the researchers entails the utilization of bilateral filtering to enhance ferrograph images of wear particles, followed by the segmentation of the enhanced images using an adaptive algorithm in order to accurately identify wear particles. Compared to conventional techniques, the utilization of this approach yields a substantial enhancement in the precision of extracting morphological characteristics and augments the dependability of wear particle pattern identification. Wang et al. introduced a sensor for detecting oil wear particles using image recognition processing, which is based on the OpenCV framework in 2022 [91]. The particle images in the hydraulic oil were preprocessed, and the contours of particle pollutants were extracted using the Canny operator edge detection algorithm. The image processing method demonstrated a recognition accuracy of 95%.

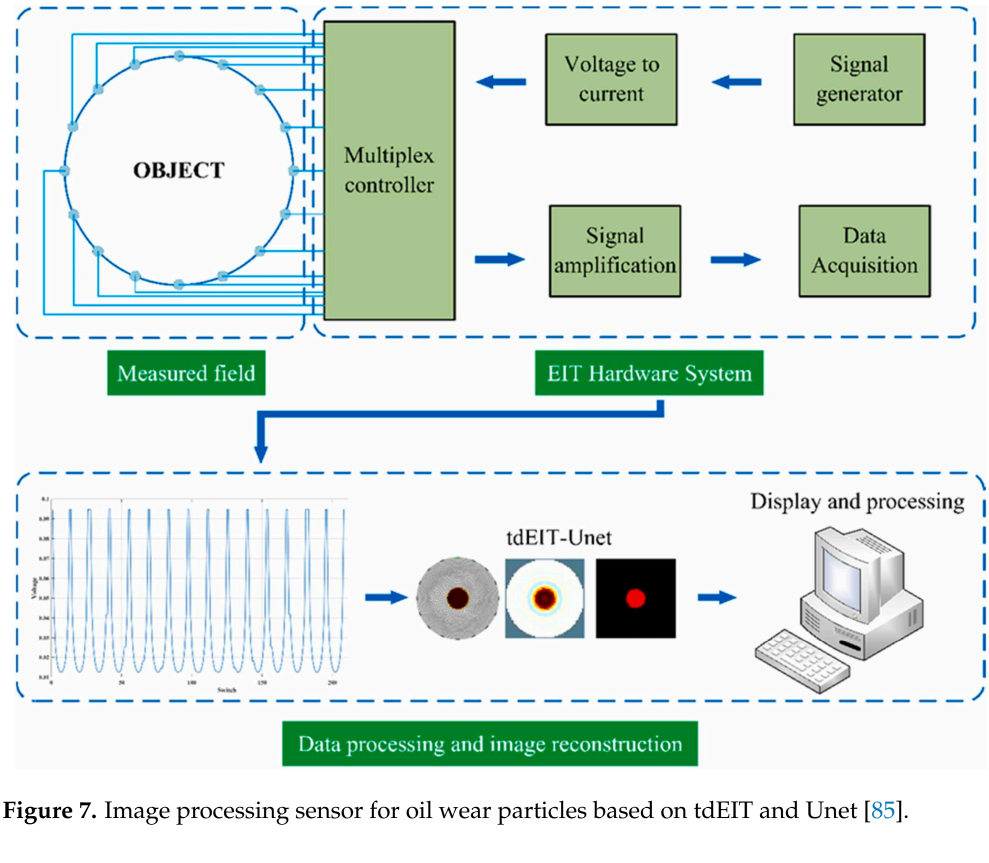
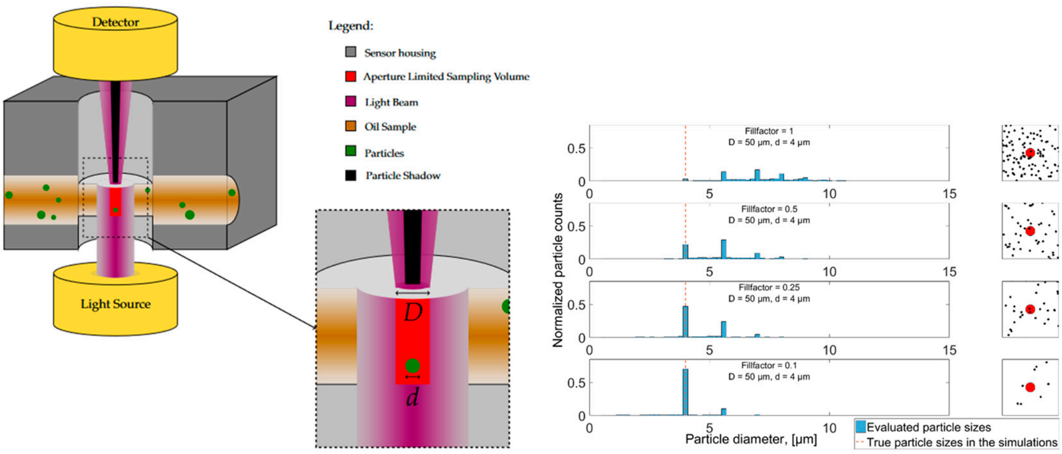


Figure 7. Image processing sensor for oil wear particles based on tdEIT and Unet [85].

3.2. Optical Sensor

The optical detection method relies on the measurement of light transmittance through the oil in order to identify and quantify different types of solid particles that are suspended within the oil. Optical sensors employ light and optics to identify and measure the presence of wear particles in the oil. Particles are identified by their optical properties, such as reflectivity and refraction. Optical sensors have proven to be efficient in detecting particles, regardless of their metallic or non-metallic composition. In 2018, Krogsøe et al. presented a novel sensor that utilized geometric optics and the light extinction principle. The researchers examined the impact of various factors, including the optical system design, particle concentration, and measurement noise, on the performance of the sensor. These investigations are illustrated in Figure 8 [92]. Simulations conducted on the sensor demonstrated that, in optimal circumstances, the correlation between the sensor aperture and the particle could be utilized to estimate the probability of effectively capturing the particle sample. However, the analysis conducted by the researchers solely focused on spherical particles and did not take into account the evaluation of particles under actual flow conditions or the consideration of light source divergence. Bastidas et al. employed an optical wear particle detection sensor with on-line measurement capabilities to identify the running-in condition of gasoline engines and evaluate the wear condition of critical component surfaces in 2023 [93]. The optical sensor demonstrates efficient detection capabilities for particles with a size of 4 microns or greater, operating at a maximum flow rate of 0.15 L/min. Nevertheless, the placement of the sensor away from the engine outlet may result in a delay in the collection of data, as the lubricating oil that enters needs time to stabilize. Additionally, optical sensors encounter difficulties in effectively differentiating air bubbles from other pollutants, thereby restricting the experimental findings to the identification of trends in the initial operational phase rather than providing precise distinctions. In 2017, Peng et al. successfully devised a microfluidic system for wear particle detection. This system utilized an optical CMOS sensor and was able to capture three-dimensional information of wear particles in real time [94]. The microfluidic system, comprising microchannels and optical CMOS sensors, demonstrates proficiency in capturing particles of varying sizes and shapes, while simultaneously providing comprehensive three-dimensional characteristics. Optical wear particle counters, which rely on light extinction, are frequently utilized in oil monitoring applications. Wu et al. developed a compact visual ferrography sensor that integrates a digital sensor with an optical CMOS image sensor, allowing for real-time monitoring of wear particles in 2009 [95]. The findings of the study suggest that the optical CMOS image sensor demonstrates effective capability in capturing wear particles of different sizes and depositing them within a confined area. By meticulously regulating the parameters, the OLVF sensor exhibits proficient deposition of wear particles of varying sizes, including both large and small particles. To validate their findings, the researchers performed experiments utilizing commercially available particle quantifiers and other instrumentation, thereby corroborating the precision and dependability of the data acquired via the OLVF sensor. Liu et al. proposed a novel approach for real-time monitoring of wear particles and oil viscosity by employing an optical oil wear particle sensor in 2022 [25]. Optical sensors were utilized to calculate physical parameters, including the velocity and diameter of wear particles within a microchannel, as well as the viscosity of the oil. A mathematical correlation was then established based on these measurements. Validation of this model through empirical investigations has demonstrated that the optical sensor exhibits the capability to reliably, efficiently, and comprehensively monitor the condition of oil in real time. Iwai et al. have developed an on-line particle counter that incorporates a photodiode for the purpose of optically detecting wear in bearing metals and carbon steel in 2010 [96]. This particle counter operates based on the principle that when a particle intersects the laser beam at a perpendicular angle, it obstructs a portion of the laser light, leading to a pulse that is detected by the photodiode. The efficacy of this on-line particle counter in monitoring the size and quantity of wear particles in circulating oil has been demonstrated. Additionally, through a comparison of the sensor's measurements with quantitative wear estimates, researchers have verified a significant resemblance, thus highlighting the sensor's dependability in analyzing wear particles. This analysis includes the assessment of their three-dimensional morphology, which is crucial for diagnosing mechanical faults.



(a) (b)

Figure 8. Optical sensor for evaluating wear particle distribution in lubricating oil systems [92]. (**a**) Detection principle of optical sensor. (**b**) A random sample of pore size and particle position was evaluated using an optical sensor for different concentrations of 4 μm particles.

3.3. Ultrasonic Sensor

The ultrasonic detection method employs particulate matter to impede and reflect the transmission of sound waves, thereby facilitating the identification of contaminants in oil. Ultrasonic sensors are utilized to emit high-frequency sound waves into the oil and subsequently measure the reflection of these waves off wear particles. By conducting an analysis of the durations of sound wave reflections and their amplitudes, these sensors have the capability to furnish valuable information regarding the dimensions and concentration of particles resulting from wear. Ultrasonic sensors have proven to be highly advantageous in the detection of larger and more densely packed particles. Through the utilization of simulation and experimental methods, Xu et al. proposed the implementation of a Quantum behavioral Particle Swarm Optimization (QPSO) technique to improve the efficiency and effectiveness of the MP algorithm in extracting the waveform characteristics of reflected ultrasonic signals in 2015 [97]. Their research findings suggest that this particular approach successfully improves the signal-to-noise ratio of ultrasonic signals, thereby facilitating the extraction of their waveform characteristics. They effectively employed these extracted ultrasonic waveform features to discriminate between various forms of wear particles and air bubbles. On the contrary, Luo et al. utilized ultrasonic sensing technology to monitor the dispersion of wear particles produced during the process of wear. By taking into account the reduction in ultrasonic energy caused by wear particles as a measure of evaluation, it has been determined that the level of wear in mechanical equipment is influenced by two factors: vibration frequency and acceleration. Weser et al. proposed a novel technique for the characterization of particles in dense suspensions by analyzing ultrasonic signals in 2013 [98]. Their innovative methodology entails the evaluation of particle characteristics through the analysis of reflected ultrasound signals. This approach provides a direct and non-intrusive means of monitoring suspensions with high concentrations, thereby presenting potential applications across diverse fields. Du et al. presented an integrated ultrasonic pulse sensor that was specifically developed for the purpose of monitoring wear particles, including both non-metallic and ferrous particles in 2013 [99]. This novel sensor, featuring a distinctive flow groove structure, ensures that all particles of wear pass through the acoustically focused region, thereby ensuring accurate particle counting. The results of their study suggest that the detection limit of the sensor can be reduced by utilizing incident ultrasonic pulses with higher center frequencies, smaller normalized focal lengths, and larger pulse amplitudes. In 2013, a study conducted by Appleby et al. examined the physical parameters associated with the degradation of lubricating oil. The researchers utilized ultrasonic measurements to analyze these parameters, as depicted in Figure 9 [100]. They utilized both theoretical derivations and experimental procedures to demonstrate the efficacy of ultrasonic measurements in the detection of wear particles, including those that are ferromagnetic, non-ferromagnetic, and non-conductive. The ultrasonic detection method employed by the researchers was able to determine particle sizes by analyzing the levels of ultrasonic signal scattering, although it was unable to differentiate between different types of wear particles. Additionally, the assessment of changes in lubricating oil viscosity can be achieved by analyzing alterations in ultrasonic signal amplitude and transit time. Thus, the application of ultrasonic sensors for monitoring wear particles in lubricating oil leads to the reflection of signals.

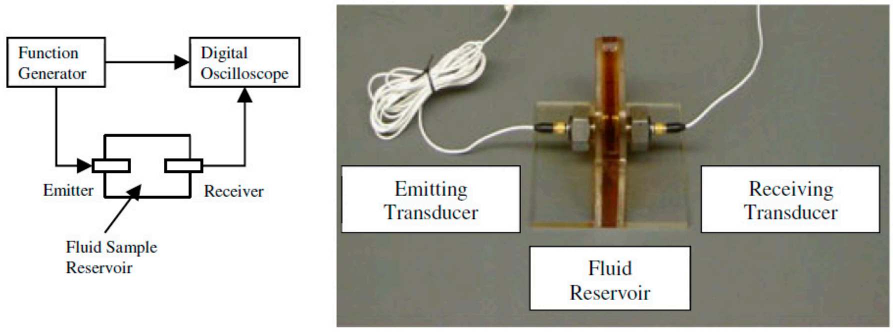


Figure 9. Ultrasonic sensors for oil viscosity and wear particle detection [100].

4. Conclusions

To address the issue of marine machinery failure in the field of marine engineering, this review aims to provide a comprehensive overview of the utilization of on-line oil wear particle detection sensors for the on-line monitoring of lubricating oil. This approach offers valuable insights and theoretical foundations for the prompt diagnosis of failures in ship rotating machinery. According to the detection principle of wear particle detection sensors, this study categorizes the sensors into two groups: electrical sensor and non-electrical sensor. It also provides a comprehensive review of the research progress in this field. Electrical sensors encompass a variety of types, including inductive, capacitive, and resistive sensors. Non-electrical sensors encompass a range of technologies, such as image processing, optical sensors, and ultrasonic sensors. These sensors possess distinct characteristics and advantages, making them extensively employed in the prompt identification of faults in rotating machinery within domains such as marine engineering and aerospace. In this paper, an overview of the aforementioned sensors is provided, and the paper also proposes the future development direction of sensors. The findings of the review indicate that while various types of sensors have demonstrated favorable outcomes in detecting wear particles, there are still challenges related to the signal-to-noise ratio and anti-corrosion performance of these sensors in high-throughput task detection, high-temperature difference environment detection, and particle aliasing detection, among others. The improvement of interference ability, signal recognition ability, sensitivity, and other related factors is still necessary. The processing technology of wear particle detection sensors necessitates urgent improvements in sensor characteristics, including miniaturization, portability, and integration. The primary objective of future research remains centered on the identification and characterization of wear particles with varying shapes at the micro-nano scale. This review offers comprehensive insights and novel ideas regarding the study of on-line monitoring sensors for detecting oil wear particles in marine equipment, specifically for the purpose of diagnosing mechanical faults in marine engineering.

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