A 3×3 wear debris sensor array for real time lubricant oil conditioning monitoring using synchronized sampling

Xiaoliang Zhu, Li Du, and Jiang Zhe

Department of Mechanical Engineering, University of Akron, Akron, OH, 44325, USA

Correspondence: Jiang Zhe, Email: jzhe@uakron.edu; Tel: 1-330-972-7737; Fax: 1-330-972-6027

Abstract

A high throughput wear debris sensor consisting of 3×3 sensing channels is presented for real time online lubricant oil conditioning monitoring. Time division multiplexing was applied to the sensing channels for measuring responses of multiple channels using one set of measurement electronics. Crosstalk among the 3×3 sensing channels was eliminated by diodes that are connected in series with each channel. Parallel L-C-R resonance was also applied to each sensing coil to increase the sensitivity. Furthermore, a unique synchronized sampling method was used to reduce the data size 50 times. Finally, we demonstrated that the sensor is capable of real time detection of wear debris as small as 50μm in SAE0W-5 at a flow rate of 460ml/min; the measured debris concentration is in good agreement with the estimated actual concentration. The design can be extended to a N×N sensor array for an extremely high throughput without sacrificing the sensitivity, and can potentially be used for real time wear debris monitoring for health condition of rotating or reciprocating machineries.

Keywords: Oil condition monitoring, Wear debris, Inductive sensor, Crosstalk, Synchronized sampling, Time division multiplexing

1. Introduction

Online condition monitoring is essential for effective and economic maintenance to avoid shutdowns and maximize the lifespans of rotating and reciprocating machines [1-2]. Many methods based on vibration, temperature or oil analysis have been used to estimate the machine's health condition [2-4]. Among them, vibration analysis has been adopted for condition monitoring of machines including damage detections of bearings and gearboxes [5], because the change in vibration signal can be connected with the dynamic characteristics of the gearbox and its fault conditions [6], e.g. defective bearings, worn gears as well as misalignment and unbalanced load. Based on pattern recognitions applied to signal's time or frequency domain, moving components' conditions can thus be determined by comparing the vibration signatures with previous signatures [7]. However, direct comparison is ineffective because different operation factors (varying load or rotation speed) affect the vibration signal generated by the rolling elements, making the

diagnosis relatively difficult [8]. In order to extract information from operation affected vibration signals, Bartelmus et al [8-12] developed a new method named load susceptibility characteristics (LSCh) to monitor the gearbox's condition in wind turbines. However, this method requires collections of extra reference data (e.g. power) with additional sensors in the system, and increases the complexity of data processing. Recently, researches have indicated that oil wear debris analysis can provide earlier warnings in the failure progression because it contains valuable information regarding the aging and damage of oil-wetted moving components [5, 13]. Studies show that the wear debris size and concentration increase gradually until the machine fails [14]. When abnormal wear begins, wear particles in the range of 50μm to 100μm are seen [15]. Thus, by monitoring the production trend of wear debris in this range, timely maintenance can be planned to avoid components break downs and catastrophic engine failures.

For wear debris sensing, while a few online wear monitoring sensors based on optical scattering [16], acoustic emission [17], capacitance sensing [18], and bulk inductive sensing [19] have been developed, their measurement accuracy is affected by oil clarity, air bubbles, harsh environment, and wear debris concentration respectively, and thus can only provide very limited information on the progression of machine wear. Most importantly, those methods cannot detect wear particles smaller than 100μm while maintaining a high throughput (>200ml/min), which is important to reflect and predict the wear debris information of the whole lubrication system. Recently, inductive pulse sensors consisting of 2-layer planar coils wound around a fluidic channel have been demonstrated for detecting ferrous and non-ferrous wear debris [20-22]. Because of the smaller sensing zone compared to the bulk inductive sensor, the inductive pulse sensor can detect individual ferrous wear particles as small as 50μm [21]. In our prior attempt to increase the throughput using only one set of detection electronics, frequency division multiplexed sensor using multiple sensing channels have been developed [22, 23]. However, because 1) all the channels are electrically connected, and 2) the bandwidth of each L-C-R resonance peak is wide, thus only up to 10 channels can be installed; otherwise crosstalk among channels would arise if a larger number of sensing channels are used, causing false positives or

Figure 1. Design concept of the 3×3 wear debris sensor array and the measurement setup

debris detection. Also, complex post signal processing or cumbersome circuit adjustment becomes inevitable for reducing the crosstalk.

More importantly, another significant challenge of the inductive pulse sensors for online oil debris analysis is their inability to process the big data generated from the sensor in real time. To accurately reflect the size and shape information about the wear debris, the complete pulse shape induced by each debris has to be detected; thus a high sampling frequency (i.e., 100MHz) has to be used to capture the complete pulse shape, ultimately resulting in a large volume of data. As an example, with a 100MHz sampling frequency, a 24.3 Terabyte data would be generated within one hour using a 10-channel sensor. It is a significant challenge to process such a large volume of data in real time, which is, however, critical for online machine condition monitoring [24]. While some online sensor networks take a measurement every 5 to 30 minutes [25, 26] to reduce the data size, this approach, if used in wear debris detection, will result in a reduced measurement accuracy in debris size and concentration (due to non-uniform and time-varying distribution of wear debris in lubricant oil during machine operation [27]), and cannot realize continuous machine condition monitoring and real time fault detection.

To overcome the above mentioned limitations, we report a unique 3×3 wear debris sensor array using synchronized sampling and time division multiplexing,

inspired by the touch sensor network technology. However, unlike the touch sensor network, in which complex virtual grounds method are used for signal reading and crosstalk suppression [28], each sensing channel was simply connected with a diode to eliminate the crosstalk effect; L-C-R resonant technique was also used on each sensing channel to improve the sensitivity. In addition to that, a novel signal processing method based on synchronized sampling, was performed for data recording. This enables collection of sensor outputs with a much lower sampling frequency without losing accurate information of wear debris, resulting in a much smaller data size. Compared with our prior works [22, 23], which can have up to 10 channels based on frequency division multiplexing, the design concept here can enable a high density sensor array (i.e., 9×9 array) without sacrificing the sensitivity and accuracy. The approaches presented here have significantly improved the throughput, reduced the data size, and enabled real time data processing, which are critical for online, continuous machine condition monitoring for long-term operations.

2. System Architecture and Operating Principle

2.1 Sensing Mechanism

Fig. 1 shows the inductive sensor array for wear debris measurement, inspired by the touch sensor network used in smart phones/tablets. Each sensing element, S_{ij} , consists of a meso-scale fluidic channel

(1.0mm in inner diameter) made of glass and a 2-layer, 20-turn planar coil wrapped around the fluidic channel. When a metallic debris particle passes a sensing channel, an inductive pulse will be generated [21], which can be measured in terms of a voltage pulse. Two multiplexers (MUX1 and MUX2) (ADG 1608) were used to connect the excitation signal to and take measurement of each sensing coil sequentially. MUX1's output terminals were connected to the three row electrodes (Row 1, Row 2, Row 3) and the input terminals of MUX2 were connected to the three column electrodes (Column 1, Column 2, Column 3). By controlling the voltage level of logic controls of MUX1 (A1, A2) and MUX2 (A3, A4), the excitation signal V_{AC} was applied to each sensing coil (S_{ij}) sequentially (see Fig. 1). In any given timeslot, only one sensing channel is active. For example, when A1=0, A2=0, A3=0, and A4=5V, Row1 and Column3 will be switched on; sensing coil S_{13} (at the top right corner) will be connected to the excitation signal. Note that the 4 logic control signals (A1-A4) should share the clock signal with the excitation source (V_{AC}) to avoid errors due to timing faults, ensuring peak values of the outputs from all 9 sensing channels are time-multiplexed into the output signal V_{out} .

For each sensing coil, S_{ij} , it can be modeled as an inductance L_{ij} in series with a resistance R_{ij} (see Fig. 2). One external capacitor, C_{ij} , was connected to each planar coil in parallel to form a parallel L-C-R resonant circuit. Each L-C-R resonant circuit will be excited by a sinusoidal excitation signal V_{AC} with a frequency of f_{AC} (2MHz). It is worth mentioning that using parallel L-C-R resonance amplifies the impedance change caused by passages of debris particles through the sensing coil/channel owing to the sharp change in impedance near the resonance frequency; hence detection sensitivity is significantly improved. Since all sensing coils are electrically connected, the impedance change of one sensing coil will cause impedance changes of other coils in the sensor array/network. For instance, when measuring the impedance of S_{13} , there are many crosstalk currents among the sensing channels, (e.g. the crosstalk current indicated by the purple dashed arrow for coil S_{22} in Fig. 1). The crosstalk among channels, if not eliminated, will cause false positive detection of wear debris. To eliminate the crosstalk between sensing coils/channels, a diode (HSMS-2700, Avago) was connected with each sensing coil in series. For a sensing coil S_{ij} , the diode only allows a forward current to pass through but blocks the reverse current that causes crosstalk. Hence when the impedance/inductance of S_{ij} is measured, the excitation signal will only pass through coil S_{ij} but not through other coils.

Figure 2. (a) Equivalent circuit of prior measurement in which only one C was connected with the coil's L-C-R circuit, and (b) equivalent circuit of the current measurement circuit in which a second resonant circuit L' - C' - R' is used.

As shown in study [20], an extra capacitor (C'_{ij}) connected in serial with the L-C-R resonant circuit can further increase the wear debris sensor's sensitivity (shown in Fig. 2(a)). However, when a diode is connected with a coil's L-C-R circuit in series, the capacitor C'_{ij} cannot be discharged because the diode prevents the current flowing backward [29]. As a result, no current passes through the sensing coil, leading to an open circuit. To solve this problem, a second parallel L' - C' - R' resonant circuit (consisting of L'_{ij} , R'_{ij} and C'_{ij}) with a much lower resonant frequency (~ 1.1 MHz) than the excitation frequency (2 MHz), was used to replace the serial capacitor C'_{ij} , as shown in Fig. 2(b). This 2nd parallel resonant circuit (L' - C' - R') permits the charge and discharge of the capacitor C'_{ij} within the L' - C' - R' circuit, while in the sensor array it behaves as a capacitor when its resonant frequency is much lower than the excitation frequency [30].

2.2 Synchronized Sampling Principle

The key for online lubricant condition monitoring is that the data analysis must be completed in real time. Here we used a real time data analysis method based on synchronized sampling to reduce the data size, based on the fact that inductive pulses caused by wear debris are represented by peak value changes of the sinusoidal output V_{out} [31].

Figure 3. Illustration of the synchronized sampling method used for the wear debris sensor array

Fig. 3 illustrates the synchronized sampling method. To perform the synchronized sampling to the output of a sensor V_{out} , 1) the digitizer (DAQ) was

synchronized with the AC excitation source; this is achieved by using the clock signal from the AC excitation source as the master time base for the digitizer (see Fig. 1), 2) set the sampling frequency the same as the excitation frequency, i.e., $T_s = T_{AC}$, and 3) adjust the phase angle of the excitation signal V_{AC} to ensure the phase angle of V_{out} to be 90° such that V_{out} reaches its positive peak value at $t=0$, $t=T_{AC}$, $t=2T_{AC}$, etc. The synchronized sampling ensures the peak values of the sinusoidal waveform (i.e. 2MHz) be collected with a much lower sampling frequency (i.e. 2MHz) than the conventional method. Thus the raw data size will be dramatically reduced. For example, using a 2MHz rather than a 100MHz sampling frequency, the data size will be reduced 50 times. In addition, synchronized sampling does not need the subsequent spline interpolation and peak detection [22, 23] to recover the precise peak values, and thus further reduces the analysis time.

3. Experiments and Discussion

The inductance (L) and resistance (R) of the fabricated 2-layer coils were measured with a precision LCR meter (E4980A, Agilent) at a frequency of 2MHz. The measurement results were listed in the first two columns of Table 1. Then a code written in MATLAB was used to calculate other parameters of the two parallel L-C-R resonant circuits (namely, C , C' , R' and L') to ensure each sensing coil reaches resonance at an identical resonance frequency (2.09 MHz). Finally, we used similar procedures described in [20] to experimentally determine the actual values of (C , C' , R' and L') to ensure each coil had the highest sensitivity near its resonance frequency. The determined capacitors and inductors were listed in Table 1, Column 3 to Column 6.

Table 1. Experimental parameters of the wear debris sensor array

Channel #	L_{ij} (μ H)	R_{ij} (Ω)	C_{ij} (nF)	L'_{ij} (μ H)	R'_{ij} (Ω)	C'_{ij} (nF)
S_{11}	0.99	0.9	5.82	10.6	3.6	1.80
		5		5	0	
S_{12}	0.82	0.8	7.00	10.3	3.4	2.16
		3		0	2	
S_{13}	0.90	0.8	6.42	10.4	3.6	1.96
		7		9	3	
S_{21}	0.85	0.8	6.74	11.1	3.2	2.04
		6		7	6	
S_{22}	0.87	0.8	6.60	10.9	4.5	2.02
		7		0	4	
S_{23}	1.03	0.9	5.64	9.98	3.9	1.76
		7			7	
S_{31}	1.03	0.9	5.64	10.5	3.1	1.74

		7		9	5	
S_{32}	0.86	0.8	6.68	9.72	3.1	2.08
		5			3	
S_{33}	0.82	0.8	7.00	10.4	3.4	2.14
		2		9	3	

3.1 Crosstalk Analysis

Figure 4. (a) Measured voltage pulses in S_{12} induced by a 162μm iron particle and a 200μm copper particle. (b) Measured crosstalk signals in the neighboring sensing element S_{11} in the sensor network. Red color: without use of diodes; blue: with the use of diodes in the sensor array.

To demonstrate the present 3×3 sensor array is able to eliminate the crosstalk effect, one 162μm iron particle and one 200μm copper particle were used to mimic two large wear debris. Each particle was fixed at the tip of a plastic fiber. For each experiment, only one channel (S_{11}) was switched on and the two particles were inserted in and pulled out at different moments of a neighboring sensing channel (S_{12}). Fig. 4(a) shows the measured voltage pulses (resulted from the inductive pulses induced by the two particles) in channel S_{12} , while Fig. 4(b) shows the crosstalk signal measured from a neighboring channel S_{11} where no particles were present. For the circuit without the diodes, the impedance change of channel S_{12} (due to passages of the two particles), caused an impedance change in the measurement channel S_{11} (crosstalk, red line in Fig. 4(b)). However, for circuit with the diodes (blue line in Fig. 4(b)), no false spikes were seen. Tests were also conducted by inserting in and pulling out wear debris in

one channel and observing responses in neighboring channels; all tested with the measurement setup in Fig. 1, no crosstalk was present. The experiment demonstrated the presented 3×3 sensor array with a serial diode connected with each sensing channel has the ability to eliminate the crosstalk current effectively.

3.2 Dynamic Measurement Setup and Signal Processing

The measurement setup is shown in Fig. 5. During normal operation, iron concentration is around 10ppm to 30ppm [32-34]. To mimic the concentration, 3.2mg iron particles with equivalent diameters between 50μm and 75μm were mixed thoroughly with 200ml 0w-5 engine oil. The iron concentration was calculated to be 19ppm; the particle concentration was calculated to fall between 9.2 and 31.1 particles/ml because of the variation in particle size. After mixing, the sample was loaded to the reservoir of the circulation system, as shown in Fig. 5. A drill pump (FPDMP21SA, Parts2O) was used to circulate the prepared sample; the flow rate was set to be (460±15) ml/min. A Keysight 33622A waveform generator was used to generate the 2MHz, 10Vpp excitation signal V_{AC} . To apply synchronized sampling to the wear debris sensor array, the phase angle of the excitation signal V_{AC} was manually adjusted to ensure the phase change of each coil's output is approximately 90° (±2°); hence peak values of all sensing channel's response were collected sequentially. The output signal was then recorded by Gage Razor™ CompuScope 14-bit Digitizer data acquisition system (DAQ) with a sampling rate of 2MHz using the waveform generator's clock time. A1 and A2, the control signals for MUX1, were two square waves (10KHz, 2Vpp, 1V offset, 1/3 duty cycle) while the control signals for MUX2, A3 and A4 were another two square waves (30KHz, 2Vpp, 1V offset, 1/3 duty cycle). It is worth mentioning here that the four control signals (A1-A4) were phase adjusted exactly as Fig. 1 shows, to make sure that during one time-slot, only one of the nine sensing channels is switched on. The four square waves also share the same clock time with V_{AC} .

Fig. 6 shows the recorded time trace of the 3×3 wear debris sensor which was recorded sequentially by the DAQ with one measurement cycle (100μs). The sequence was controlled by the four logic control signals (A1-A4). The difference in baseline output voltages from the 9 sensing channels in Fig. 6 was caused by the difference in each channel's impedance. It can also be noted that when one channel was switched on, there was a glitch noise followed by a transient response with a settling time of approximately 4μs, as shown in the inset of Fig. 6, which was caused by on and off of the control signals and the response of each L-C-R circuit [35]. The data points within the glitch and the transient response were removed to recover

individual inductive pulses from each channel. Note that with the small measurement cycle (100μs), each inductive pulse caused by a debris, typical with a pulse duration of ~5ms, is expected to have 50 data points. Hence the shape of every single pulse can be accurately recovered.

Figure 5. Measurement setup of the 3×3 wear debris sensor array (Length 14cm, Width 16cm, Height 8cm) with the following components: 1. Signal input/output, 2. Control signal A1, 3. Control signal A2, 4. Control signal A3, 5. Control signal A4, 6. Multiplexer power inlet (DC, 13.0V), 7. MUX2, 8. Multiplexer channel enable voltage (DC, 3.6V), 9. MUX1, 10. Oil inlet, 11. Flow divider, 12. Sensing channel, 13. Reservoir, 14. Oil outlet

Figure 6. Measured raw voltage trace from the 3×3 wear debris sensor in one measurement cycle

To obtain each channel's response, first, baseline detection algorithm was conducted to detect the plateau portion of each channel (blue data points in Fig.

6). After that, the detected points of each channel were averaged (red triangles in Fig. 6). Each red triangle represents one channel's response during its switch-on time. All the averaged points were then regrouped in to nine subsets sequentially, representing peak values from each channel. Finally, for each subset, four layers of 1D stationary wavelet transform (SWT) was performed in MATLAB to improve the signal-to-noise ratio. It is worth mentioning here that for 1s measurement, the usage of 2MHz synchronized sampling has dramatically decreased the data size from 675MB (with 100MHz sampling rate) to 13.5MB; the data processing time is also decrease from appropriately 17.8mins to 4.3s compared with the data processing method based on frequency division multiplexing [22, 23]. It is worth mentioning the soft data processing can be replaced by an onboard hardware. By setting a threshold value for the hardware, only the pulses exceeding the noise level are recorded; hence the data size can be further reduced. Due to the sparse distribution of wear debris in the lubrication oil even at severe wear conditions [32, 33], only less than 10% [23,27,34] of the sensor response contains the wear debris information. Hence, the data processing time is expected to be reduced below 1 second. The small data size and the fast data processing make the wear debris sensor possible for real time online machine health monitoring

3.3 Measurement Results

Fig. 7 shows the voltage pulses measured for channel 1 to channel 9 when a sample containing iron particles between 50 μ m and 75 μ m was tested with the sensor. Each pulse higher than the maximum noise level ($\pm 0.009\%$), which was measured with a sample containing no iron particles, represents one wear particle passing through a sensing channel. The differences in pulse height are primarily due to the particle size differences; the larger the particle, the higher the pulse. The concentration of the wear debris was calculated by dividing the number of pulses by the oil volume passing through the sensor array within the same period of time. Under a flowrate of (460 $\pm$ 15)ml/min, a total of 1640 spikes were detected within 16s, which corresponded to a concentration of (13.4 $\pm$ 0.4) particles/ml. This value is in good agreement with the actual particle concentration which was estimated to be between 9.2 and 31.1 particles/ml, demonstrating the present wear debris sensor can measure oil debris accurately. It is worth pointing out that the present wear debris sensor can also differentiate ferrous and nonferrous particles (i.e. copper or aluminum). When nonferrous particles passing through the sensing zone, the coil's inductance will decrease because of the eddy current effect, thus voltage pulses with negative polarities will be generated (as shown in Section 3.1 Fig. 4). This test demonstrated that

with the synchronized sampling and time division multiplexing methods, the wear debris sensor can simultaneously detect wear debris from all sensing channels with a high accuracy.

Figure 7. Measured voltages pulses for each sensing channel of the 3×3 wear debris sensor

To further test the system's ability for wear debris monitoring, three additional samples with different iron particle weights and diameter ranges were prepared using steps that stated in Section 3.2. Each sample was tested three times under a flow rate of (460 ± 15) ml/min. Note that for most engine oils, an iron concentration larger than 30ppm typically indicates the machine is in a severe condition [34]. As shown in Fig. 8, testing results have shown that the measured particle concentrations were all in good agreement with the estimated particle concentration (light blue and light purple shaded areas). These testing results demonstrated that the present 3×3 wear debris sensor is capable of accurately detecting wear particles with different size and concentration, indicating that the sensor can be potentially used for online wear debris monitoring.

Figure 8. Measurement results of iron particle concentrations of four samples. Blue circles represent measured concentration of 3.2mg and 6.0mg iron particles between 50μm and 75μm; red triangles represent measured concentration of 4.5mg and 4.9mg iron particles between 75μm and 105μm. Light blue and

light purple shaded areas represent the estimated concentration ranges.

The significance of using the 3×3 oil debris sensor array is that it only requires one signal input and one signal output for all the sensing channels. In addition, it permits integration of a larger amount of channels to increase the throughput without crosstalk effect. Other oil property sensors like water content sensor or viscosity sensor can also be installed to expand the sensor's capability. Note that the transit time of each wear debris through a sensing coil is around 5ms (corresponding to 200Hz) with a flowrate of 460ml/min (51ml/min. per channel). From our measurement, an inductive pulse can be represented by 10 data points without sacrificing accuracy; hence the maximum time interval between two adjacent data points for one channel is $5\text{ms}/10 = 500\mu\text{s}$. On the other side, the minimum time interval for data collection of one data point of each channel is $6\mu\text{s}$ ($5\mu\text{s}$ settling time (see Fig. 6) and $1\mu\text{s}$ for 2 data points recording). Thus the sensor array can accommodate up to 83 sensing channels ($500\mu\text{s}/6\mu\text{s} \approx 83$) without sacrificing accuracy. Therefore, the design concept can be extended to a 9×9 sensor array to achieve a flowrate of 4.1L/min. The ability of detecting wear debris in such a large flow rate is needed for online health monitoring of large rotating machines [36]. Because of using the synchronized sampling, adding more sensing channels would not increase the data size and the processing time.

4. Conclusion

We demonstrated a proof-of-concept 3×3 wear debris sensor for detecting wear debris particles in lubrication oil. Time division multiplexing in combination with series diodes were used to obtain each channel's response sequentially without crosstalk effect. Synchronized sampling was also utilized to significantly reduce the data size and the data processing time without sacrificing the sensitivity and accuracy. The present wear debris sensor can accurately measure wear particles as small as 50μm at a high flowrate (460ml/min). The design concept can be extended to a 9×9 sensor array to analyze wear debris lubricant with a higher flowrate, 4.1L/min. With its compact structure, high sensitivity, fast data processing, and high throughput, this sensor array has a potential to provide real time wear debris information about the lubrication oil, which is important for online machine health monitoring.

Acknowledgements

This work is partially supported by the National Science Foundation under award #1200032 and #1353720.

References

- [1] Antoniadou I., et al. "Aspects of structural health and condition monitoring of offshore wind turbines." *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **373**, no. 2035 (2015): 20140075.
- [2] Bartelmus W., and Zimroz R. "Vibration condition monitoring of planetary gearbox under varying external load." *Mechanical Systems and Signal Processing*, **23**, no. 1 (2009): 246-257.
- [3] Younus A. M., and Yang B. S. "Intelligent fault diagnosis of rotating machinery using infrared thermal image." *Expert Systems with Applications*, **39**, no. 2 (2012): 2082-2091.
- [4] Khan M. A., and Starr A. G. "Wear debris: basic features and machine health diagnostics." *Insight-Non-Destructive Testing and Condition Monitoring*, **48**, no. 8 (2006): 470-476.
- [5] Márquez F. P. G., et al. "Condition monitoring of wind turbines: Techniques and methods." *Renewable Energy*, **46** (2012): 169-178.
- [6] Baydar N. and Ball A. "A comparative study of acoustic and vibration signals in detection of gear failures using Wigner–Ville distribution." *Mechanical systems and signal processing*, **15**, no. 6 (2001): 1091-1107.
- [7] Lebold M. et al. "Review of vibration analysis methods for gearbox diagnostics and prognostics." *Proceedings of the 54th Meeting of the Society for Machinery Failure Prevention Technology*. Vol. 634. 2000.
- [8] Zimroz R. et al. "Diagnostics of bearings in presence of strong operating conditions non-stationarity—a procedure of load-dependent features processing with application to wind turbine bearings." *Mechanical Systems and Signal Processing*, **46**, no. 1 (2014): 16-27.
- [9] Bartelmus W., and Zimroz R. "A new feature for monitoring the condition of gearboxes in non-stationary operating conditions." *Mechanical Systems and Signal Processing*, **23**, no. 5 (2009): 1528-1534.
- [10] Bartelmus W. et al. "Modelling of gearbox dynamics under time-varying nonstationary load for distributed fault detection and diagnosis." *European Journal of Mechanics-A/Solids*, **29**, no. 4 (2010): 637-646.
- [11] Zimroz R. et al. "Measurement of instantaneous shaft speed by advanced vibration signal processing-application to wind turbine gearbox." *Metrology and Measurement Systems*, **18**, no. 4 (2011): 701-712.
- [12] Bartelmus W. "Root cause and vibration signal analysis for gearbox condition monitoring." *Insight-Non-Destructive Testing and Condition Monitoring*, **50**, no. 4 (2008): 195-201.
- [13] Kumar M., Shankar Mukherjee P., and Mohan Misra N. "Advancement and current status of wear debris analysis for machine condition monitoring: a review." *Industrial Lubrication and Tribology* **65** no. 1 (2013): 3-11.
- [14] Stachowiak G., and Batchelor A. W. *Engineering tribology*. Butterworth-Heinemann, 2013.
- [15] Tucker J. E., et al. "LASERNET fines optical wear debris monitor: A navy shipboard evaluation of CBM enabling technology." *54th Mach. Fail Prev. Technol. Proc.* **191** (2000).
- [16] Haiden C., et al. "A Microfluidic Chip and Dark-Field Imaging System for Size Measurement of Metal Wear Particles in Oil." DOI: 10.1109/JSEN.2015.2501355, (2015).
- [17] Loutas T. H., et al. "The combined use of vibration, acoustic emission and oil debris on-line monitoring towards a more effective condition monitoring of rotating machinery." *Mechanical Systems and Signal Processing*, **25**, no. 4 (2011): 1339-1352.
- [18] Murali S., et al. "Capacitive Coulter counting: detection of metal wear particles in lubricant using a microfluidic device." *Smart Materials and Structures*, **18**, no. 3 (2009): 037001.
- [19] Flanagan I. M., Jordan J. R., and Whittington H. W. "An inductive method for estimating the composition and size of metal particles." *Measurement Science and Technology*, **1**, no. 5 (1990): 381.
- [20] Du L., et al. "Improving sensitivity of an inductive pulse sensor for detection of metallic wear debris in lubricants using parallel LC resonance method." *Measurement Science and Technology*, **24**, no. 7 (2013): 075106.
- [21] Du L., and Zhe J. "A high throughput inductive pulse sensor for online oil debris monitoring." *Tribology International*, **44**, no. 2 (2011): 175-179.
- [22] Du L., et al. "High throughput wear debris detection in lubricants using a resonance frequency division multiplexed sensor." *Tribology Letters*, **51**, no. 3 (2013): 453-460.
- [23] Zhu X., Du L., and Zhe J. "An integrated lubricant oil conditioning sensor using signal multiplexing." *Journal of Micromechanics and Microengineering*, **25**, no. 1 (2015): 015006.
- [24] Yan R., and Gao R. X. "Approximate entropy as a diagnostic tool for machine health monitoring." *Mechanical Systems and Signal Processing*, **21**, no. 2 (2007): 824-839.
- [25] Yao Y., et al. "Online anomaly detection for sensor systems: A simple and efficient approach." *Performance Evaluation*, **67**, no. 11 (2010): 1059-1075.

- [26] Hasenfratz D., Saukh O., and Thiele L. "Model-driven accuracy bounds for noisy sensor readings." IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS), 2013.
- [27] Agarwal A. K., Bijwe J., and Das L. M. "Wear assessment in a biodiesel fueled compression ignition engine." Journal of Engineering for Gas Turbines and Power, **125**, no. 3 (2003): 820-826.
- [28] Saxena R. S., et al. "Crosstalk suppression in networked resistive sensor arrays using virtual ground technique." International Journal of Electronics, **100**, no. 11 (2013): 1579-1591.
- [29] Ruan X., and Yan Y. "A novel zero-voltage and zero-current-switching PWM full-bridge converter using two diodes in series with the lagging leg." IEEE Transactions on Industrial Electronics, **48**, no. 4 (2001): 777-785.
- [30] Paranjothi S. R. Electric Circuit Analysis. New Age International (P) Limited, 2009.
- [31] Du L., and Zhe J. "Parallel sensing of metallic wear debris in lubricants using under-sampling data processing." Tribology International, **53**, (2012): 28-34.
- [32] Zararsiz A., Kirmaz R., and Arikan P. "Determination of wear metals in used lubricating oils by X-ray fluorescence spectrometry." Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, **108**, no. 4 (1996): 385-388.
- [33] Macian V., et al. "Analytical approach to wear rate determination for internal combustion engine condition monitoring based on oil analysis." Tribology International, **36**, no. 10 (2003): 771-776.
- [34] Isaa M. C., et al. "Ferrographic analysis of wear particles of various machinery systems of a commercial marine ship." The Malaysian International Tribology Conference. 2013.
- [35] Heinz E., et al. "Dynamic behavior of dc SQUIDs in time-division multiplexing readout schemes." Superconductor Science and Technology, **26**, no. 4 (2013): 045013.
- [36] Dempsey P. J. "Integrating oil debris and vibration measurements for intelligent machine health monitoring." NASA TM 211307 (2003).