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Experimental study on inductive method for online material loss detection with high debris concentration

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Abstract. Online Oil debris detection is a complex and systemic issue that multiple requirements should be met for a practical application. When severe wear or tear happens, more accurate detection is needed for higher debris concentration. Aiming at promoting detection accuracy under the practical high debris concentration conditions, in this work, an experimental study is carried out to test the performance of an inductive oil debris detection method using a multi-channel sensor based on dual excitation sources with serial layout. Ferrous powders with different sizes and amounts are used for the experiment. Data processing methods including band-pass filter and anti-aliasing techniques are used for optimizing the estimation. The tested results indicate that the counting accuracy of coarse iron powder with 2.5 g/L concentration hydraulic oil at a flow rate of 40 L/min is higher than 85.8% and by data processing, the accuracy is promoted by 21.4% averagely.

1. Introduction

Wear and tear unavoidably brings about material loss [1]. By ferrography [2], people started to establish the relationship between debris features and characteristics of material loss [3]. Nowadays online debris detection methods were introduced and debris analysis has become a powerful approach for interpreting material loss and providing prognostic information. Existing methods include optics, capacitance, resistance, ultrasonic, x-ray and inductive methods [4]. Compared with the other methods, the inductive sensors are usually easily-installed on oil pipes and able to differentiate ferrous debris from non-ferrous debris [5].

Research studies [4,6] indicate that for engineering applications the sizes of debris usually range from $1\mu m$ to $150\mu m$ under normal work conditions. When severe wear happens, the sizes of debris will follow a different distribution. Several inductive sensors have been designed to promote the detection precision. Hong *et al* [7] proposed a radial inductive sensor which can detect $20\mu m$ thick ferromagnetic debris in 20 mm diameter pipes. Li *et al* [8] introduced a high throughput inductive pulse sensor which is able to detect $50\mu m$ debris in lubrication oil with a high throughput. Zhu *et al* [9] utilized a sensor array which is able to detect debris at a flow rate of 460 mL/min. High precision means identifying more debris from the same contaminative oil. High throughput results in short time-interval, which will influence the detecting performance. Large diameter pipes will reduce the intensity and uniformity of magnetic field. To cope with these problems, data processing methods are employed. Band-pass filter and correlation algorithm may be used to improve signal-to-noise ratio [10]. Degenerate unmixing estimation technique can be used for aliasing signals separation [11]. The accurate detection for high concentration of debris should, then, be regarded as a systematic issue instead of focusing on structure designing or other individual aspects.

In this work, we designed an experiment setup to test the systematic performance of a former proposed inductive method [5] with a practical high throughput. The test results are compared with results processed using the aforementioned data processing techniques, aiming to identify potentially problems for practical online applications. The experimental procedure is presented in Section 2 and the results are elaborated in Section 3. Conclusion is drawn in Section 4.

2. Experimental procedure

The prototype of the inductive debris detection sensor based on dual excitation sources [5] is shown in **Figure 1**(a). Each sensor is designed with two channels whose outputs are theoretically equal but practically different because of noise. As is shown in **Figure 1**(b), hydraulic oil flows in the system driven by an axial piston pump. Motor connected to the pump is used to control the flow rate. Two sensors are installed serially on a 10 mm diameter pipe. Debris are injected into an injection device with the switch off. When the test begins, the switch is turned on and the debris flow with hydraulic oil into the tested part. Before and after the tested part, two oil filters are set to exclude the interaction among test groups. Signals are collected by a data acquisition device connecting to the computer.

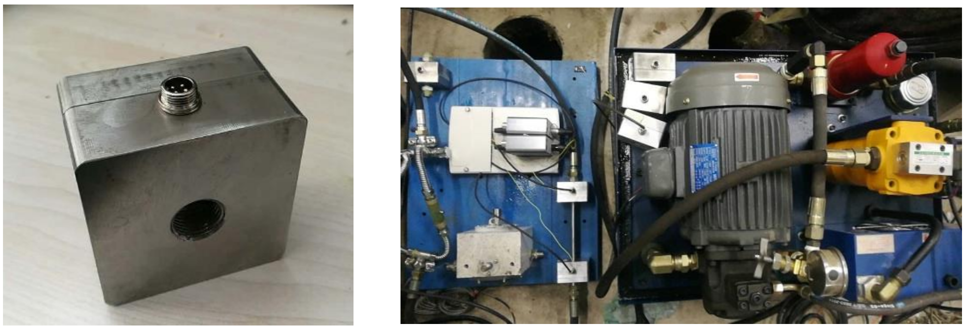
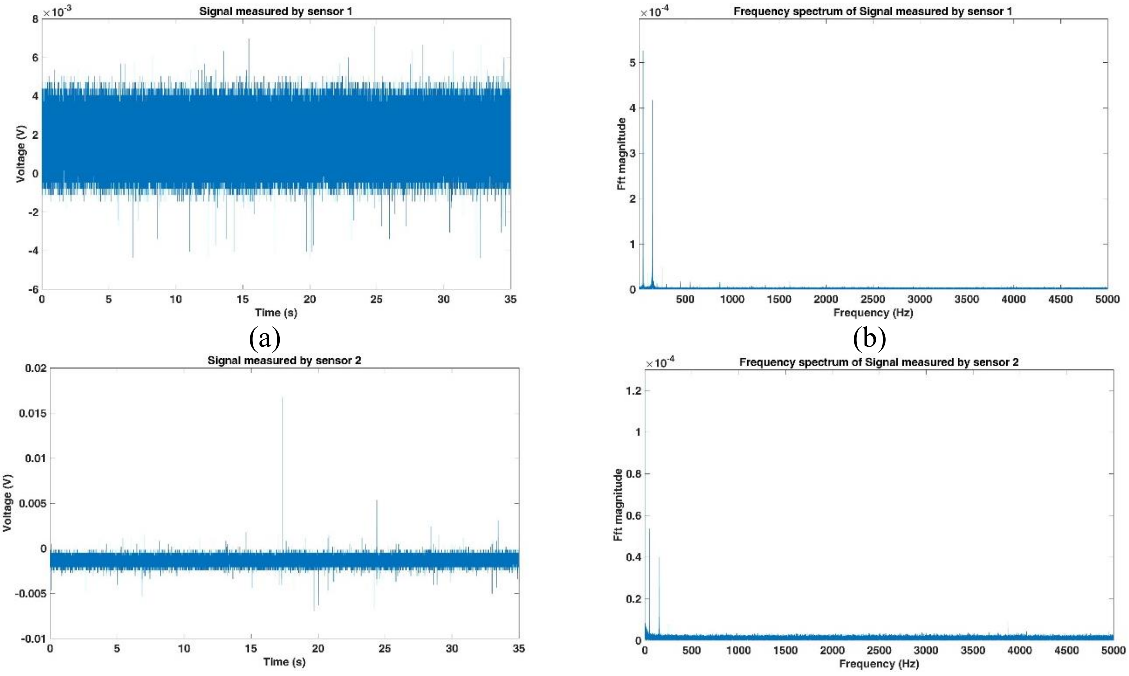

(a) (b)

Figure 1. Sensor and experiment setup.

The output pressure of the pump is 0.7 MPa. The flow rate is approximately 40 L/min which is close to the practical work condition and much larger than the laboratorial test conditions. The sample frequency of the data acquisition device is 10 kHz. Two types of iron powders are used for the test. The size of medium powder ranges from $50\mu m$ to $100\mu m$ and that of coarse power ranges from $150\mu m$ to $500\mu m$. The injection switch is turned on after the system runs 10 seconds for each test. An instantaneous fluid with high debris concentration will pass through the tested pipe. After each test group, the system runs for a while, so that the remaining powders flow away from the injection device and the powders are well-filtered by the oil filters.

3. Experimental results

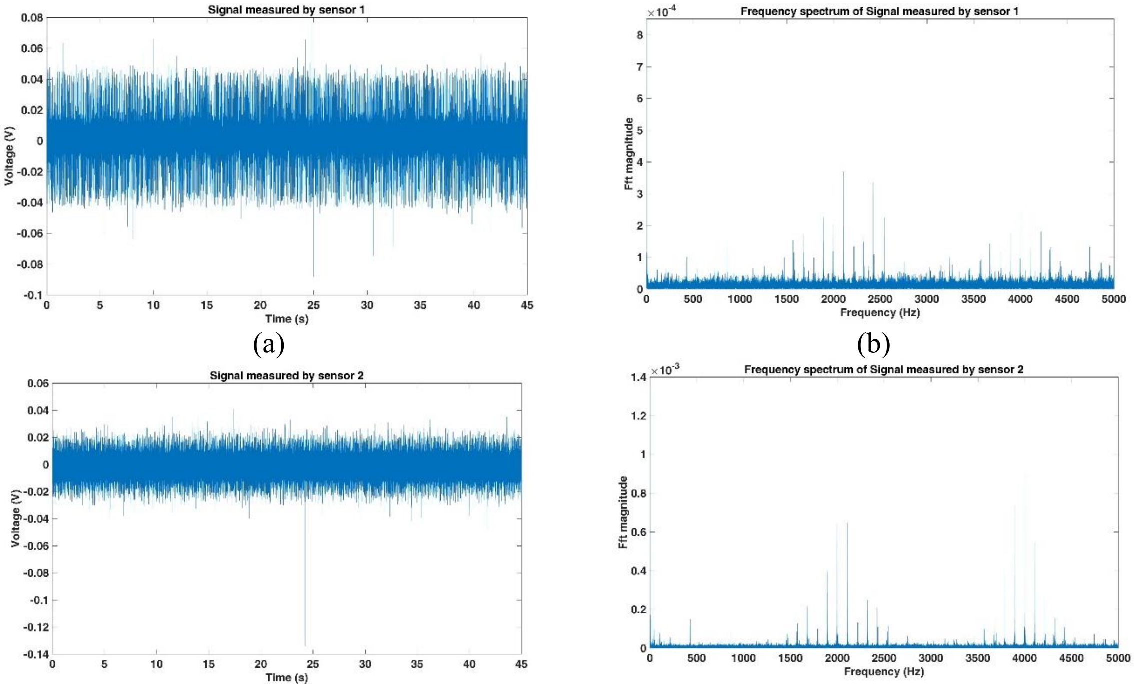
Iron powders were employed to replace real abrasive debris. For the first test group, the pump was not started, signals from the two sensors were collected as shown in **Figure 2**. **Figure 2**(a) displays the signal from sensor 1. By converting the time domain data into frequency domain data, the frequency spectrum can be obtained as shown in **Figure 2**(b). It can be seen that the time domain data are noisy, but there are two strong peaks at 50 Hz and 150 Hz in the frequency domain. Obviously, the peak at 50 Hz is caused by the electromagnetic interference from commercial electrical power. Since no other device runs during the test, 150 Hz is caused by the harmonic interference from three-phase electric. Weak peaks can be found at each harmonic frequency like 250 Hz. **Figure 2**(c) displays the signal from sensor 2 and the corresponding converting result by discrete Fourier transformation can be found in **Figure 2**(d).



(a) (b)

(c) (d)

Figure 2. Experiment results when the pump stops.



(a) (b)

(c) (d)

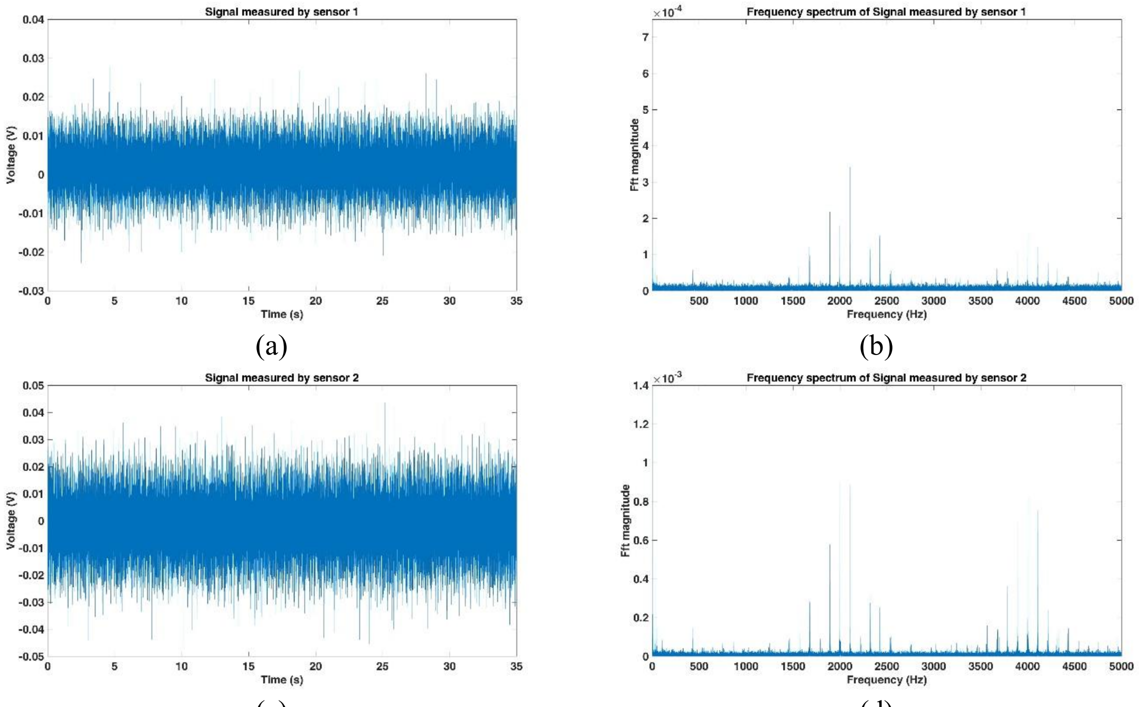
Figure 3. Experiment results without debris.

For the second test group, the pump started running but no powders were injected to the system. Signals measured by sensor 1 can be seen in **Figure 3**(a) and the corresponding frequency spectrum is shown in **Figure 3**(b). Compared with the first group, strong peaks occur at higher frequency near 2000 Hz, which is caused by the periodic rotation of the piston pump. Its harmonic interference occurs near 4000 Hz. **Figure 3**(c) displays the signal from sensor 2 and the corresponding convert result by discrete Fourier transformation can be found in **Figure 3**(d). Obviously, the method is sensitive to the vibration which is commonly seen in practical conditions.

Table 1. Experiment results.

Group	Debris	Concentration	Reference	Sensor 1	Sensor 2	Optimized result	Error
3	1g Medium	250mg/L	1.6×10^4	5893	5416	7504	0.531
4	2g Medium	500mg /L	3.2×10^4	6798	6545	12960	0.595
5	4g Medium	1g/L	6.4×10^4	15890	16341	27008	0.578
6	10g Medium	2.5g/L	1.6×10^5	25621	26848	49120	0.693
7	1g Coarse	250mg/L	600	436	401	552	0.08
8	2g Coarse	500mg /L	1200	726	792	1055	0.121
9	4g Coarse	1g/L	2400	1489	1450	2100	0.125
10	10g Coarse	2.5g/L	6000	4256	4534	5148	0.142

For group 3 to group 10, iron powders with different amounts were injected into the system. The parameters for each group are listed in **Table 1**. In group 3 to group 6, medium powders were tested and in group 7 to group 10, coarse powders were tested. The theoretical amount of powders is estimated by assuming that the density of the iron powders is 3 g/cm^3. The results of group 7 are shown in **Figure 4**. Unlike the results collected in laboratory conditions, all that can be seen is a noisy waveform that conveys little information. From the frequency domain, no evident difference can be found compared with the result shown in **Figure 3**.



(a) (b)

(c) (d)

Figure 4. Experiment results with debris.

The induced voltages by debris are aperiodic sine-like waveforms whose frequency is around 100 Hz. According to the aforementioned methods, a 200-order digital band-pass filter using hamming window is designed as is shown in **Figure 5**. The range of the pass band is from 70 Hz to 130 Hz. The filter is implemented by MATLAB Filter Designer. The filtered results of the signals shown in **Figure 4**(a) and **Figure 4**(c) are shown in **Figure 6**(a) and 6(b), respectively. The filtered results are much distinct than the unfiltered results. It can be seen that at 10s, the powders were injected into the oil and about 2 seconds later, both the two sensors detected the debris. Obviously, some induced voltages are superimposed and noise by the harmonic interference still exists. By counting the peaks, the amount of debris can be obtained directly. The corresponding results are listed in **Table 1**.

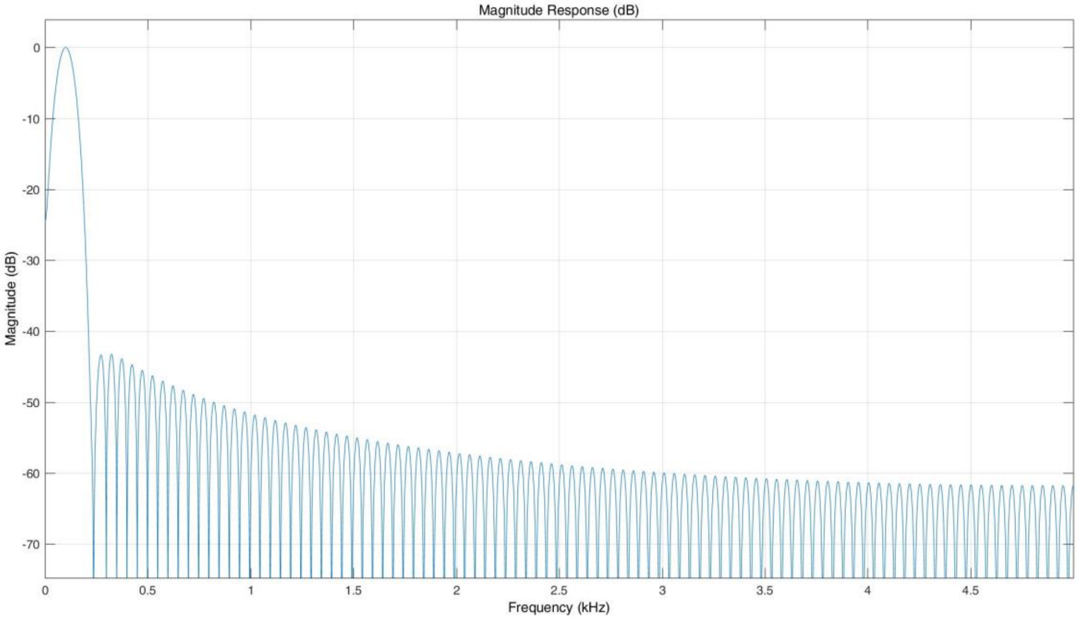
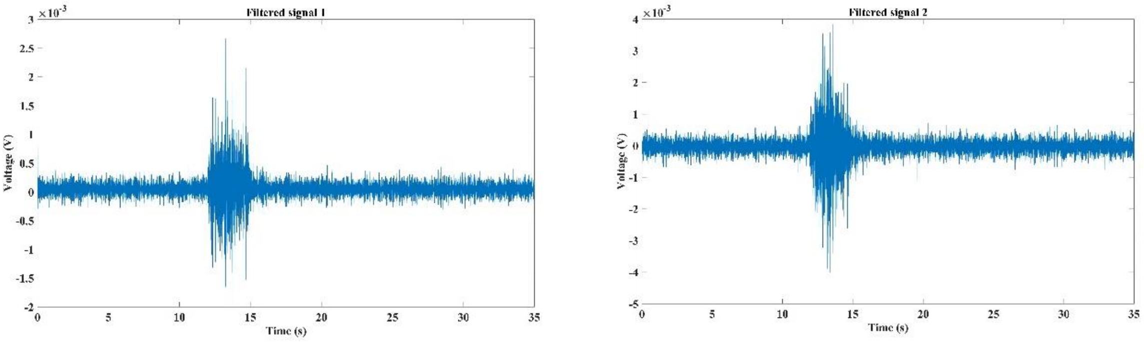


Figure 5. The designed band-pass filter.



(a) (b)

Figure 6. Filtered signals.

The estimated amount of debris work is as the references. The concentration is calculated by assuming that all the debris pass through the two sensors in 3 seconds. By counting the peaks directly, results from the two sensors are similar. Generally, the accuracy for coarse powder detection is better than the accuracy for medium powder detection. The performance for less debris is better than the performance for larger amount of debris, which is in accordance with the former experimental result. But the amounts estimated by sensor 1 are not always larger than sensor 2, which means that the differences between the two sets of results are not caused by the inherent discrepancy of the two sensors. More probably, the relative phase differences among debris change with the flowing viscous fluid. Methods structured with sensor arrays may suffer from the same problem, while the multi-channel methods [9] display good performance.

Well-designed sensors may integrate multi-channel and band-pass techniques, which will resist extraneous interference largely. However, the intrinsic aliasing problem caused by the high throughput cannot be precautionary. Post-processing is an indispensable part of this systematic issue. Here, we employed an anti-aliasing method based on degenerate unmixing estimation technique [11]. The superimposed signals are firstly separated and then, the amounts of debris are estimated from the optimized results. The error is calculated by

$$\text{Error}=1-\frac{\text{Optimized result}}{\text{Reference}}. \tag{1}$$

By conducting the anti-aliasing method, the detecting accuracy is improved compared with counting the peaks directly. The error increases with the increasing of amount of debris. The average accuracy promotion for the coarse powder detection is about 21.4%, and that for the medium powder detection is about 15.6%. The anti-aliasing optimization method is likely to be more effective for larger debris with lower concentration. This also indicates that the aliasing problem is more severe in high-throughput and high-precision conditions. After optimization, the method provides us acceptable results for large debris particles. However, the existing methods nearly fails in detecting medium powder with high-aliasing accurately.

4. Conclusion

Online inductive oil debris detection method is able to measure material loss in oil flow, which provides high-efficiency interpretation of material properties. By promoting the detection precision, small debris can be detected, in the meanwhile, the stronger effect of noise and the higher possibility of debris superimposition can no more be ignored. Therefore, simply pursuing the higher precision will provide less value for practical applications. The intrinsic aliasing of debris should also be considered as well as identifying useful signals from noise. Meanwhile, in practical application, the oil flow with high debris concentrations are commonly seen and external vibration and harmonic interference will be mixed in the ideally laboratorial signals. The practical signals may need more engineering techniques to recover the laboratorial level.

In this study, the inductive method is adapted on a real engineering application. Ferrous powders are used to present material loss. Combining the band-pass filter and anti-aliasing technique, the method is able to count coarse powder with minimum accuracy of about 85.8%. The method does not display good performance in counting medium powders that the maximum accuracy is about 46.9%.

Future works may concern promoting small debris detection accuracy with a relative high debris concentration by more effective noise control means.

Acknowledgments

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