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Design a Condition Monitoring System for Rotating Machinery Gearboxes by Oil Quality Measurements and Vibration Analyses

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***Abstract*— Every year high costs are expending to repair rotating machinery in factories and industrial centers due to failures. Most failures happen suddenly while by condition monitoring of systems prognosis and diagnosis are possible. By condition monitoring, the failures can be detected and solved in the early stages. Gearboxes are an element used widely, and applying condition monitoring for them makes a significant benefit for saving budget due to prognosis and removing failure before progress. The current paper aims to present a condition monitoring system for gearbox which is able to inspect lubricant by oil temperature and pH. Moreover, it can detect some defects in the gearbox by vibration analyses such as unbalance, bent shaft, looseness in bearing housing, and whirl of oil. The evaluation of the system shows that its accuracy is proper for use in gearboxes.**

Keywords*— *Condition Monitoring, Gearbox, Vibration Analysis, Temperature Measurements, pH Metering, Curve Fitting

I. Introduction

Failure happening imposes high costs on machinery, and it leads to an interruption in production. One of the mechanical components in rotating machinery is gearboxes which are faced with damage and failure in the long term. Consequently, production delays are a result of that, and repair costs and profit reduction may be increased. To avoid unexpected failure and breakdown, detecting problem is more imperative. As a result of this demand, the condition monitoring process is more important for researchers in gearbox development. They enable detection of gear cracks and failure during testing and stop the test before the gear crack progresses. After that, the investigators are able to identify where the failure began in the early stages and decide about the reason for the gearbox fault. Therefore, the designers can take appropriate steps in gearbox design to improve gearbox performance. Condition monitoring can minimize the time of problem finding and solving that while a shutdown of a machine is not compulsory. Whereas condition monitoring is a wide area, many investigations are carried out by various methods on different components. Condition monitoring systems based on vibration analysis can monitor all parts of gearboxes such as gearing, bearings, and shafts. Gearboxes are employed in rotating machinery to change angular velocity between several parts. Thus, applying condition monitoring (CM) make notable benefits to avoid local and global failure in gearboxes. Most CM approaches are based on oil analysis. Some of them utilize vibration and angular motion analysis or mathematical modeling.

Time statistical analysis is one of the popular methods in gearbox CM [1]. In this technique, some factors are employed to study the behavior of the system such as Root Means Squared, Kurtosis, Crest Factor, etc. [2]-[5]. In addition, to study high-frequency response in rotary systems, the enveloping method is applicable [6][7]. Recently, Wavelet analysis is concentrated by researchers [8]-[12] in beside of Fast Fourier Transformation to study systems in frequency domains [13][14]. In fact, by the energy method, the wavelet can show variations of response in time and frequency domain together. In this paper, the main objective is to establish a low-cost CM system to inspect lubricant quality, temperature, and gearbox diagnosis via vibration analysis.

II. Description of Gearbox Condition Monitoring

As stated previously, three features have been considered for this gearbox condition monitoring system:

1- Vibration observation to fault detection
2- Detection oil lubricant pH by the novel sensor
3- Measuring oil temperature

Thus, by these three parameters (lubricant quality, lubricant temperature, and gearbox vibration) condition monitoring can be applied effectively. A data collector system was designed and fabricated to record three parameters of the gearbox as depicted in Fig. 1.

Fig. 1. The fabricated gearbox condition monitoring

An accelerometer (ADXL 335) is used for sensing the vibration of the gearbox. Additionally, a temperature module (LM35) is employed to detect lubricant temperature in the gearbox tank. Also, a pH sensor was fabricated to observe oil electrical conductivity. An Arduino mega board is located in the box as a data logger board.

A. Fault Detection by Vibration Analysis

Firstly, the vibration analysis of this gearbox condition monitoring system is described. A recognizer program written in the MATLAB software compares acceleration signals with reference patterns. Next, by this comparison, the type of faults can be discovered. In fact, a curve fitting method used to check the compatibility of a vibration signal to benchmark signal by simple Non-linear least squares is employed as:

$$f(x) = \frac{1}{2}\sum_{i=1}^{m} r_i\,(x)^2 \qquad (1)$$

Where $x \in R, i = 1, \ldots, m$.

Five reference patterns are considered to compare with the recorded signal of the gearbox:

- Signal of unbalance fault
- Signal of a bent shaft
- Signal of misalignment
- Looseness changes normal signal
- Generated signal due to oil whirl

Fig. 2 to Fig. 6 demonstrates reference pattern signals for typical fault; bent shaft, unbalance, looseness, misalignment, and oil whirl, respectively. Therefore, the system software can compare the acceleration collected signal to the reference signals and recognize the type of fault in the gearbox.

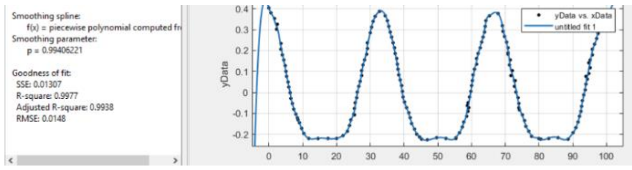

Fig. 2. Reference signal for bent shaft

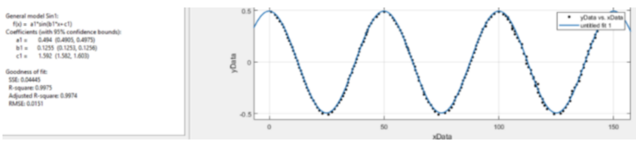

Fig. 3. Reference signal for unbalance shaft

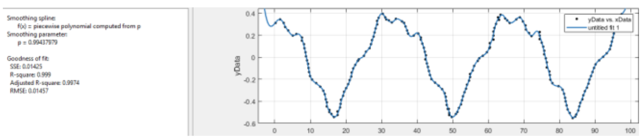

Fig. 4. Reference signal for looseness in the shaft

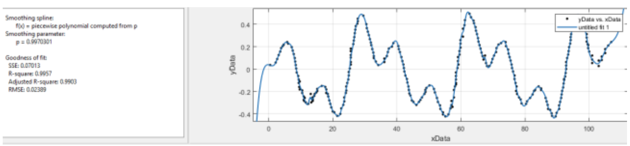

Fig. 5. Reference signal for misalignment fault in the shaft

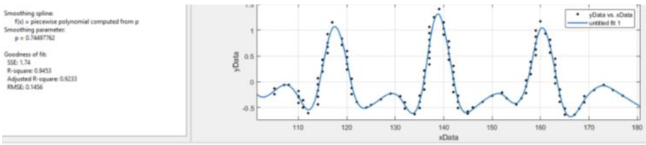

Fig. 6. Reference signal for oil whirl in the gearbox

B. Measurement of Lubricant pH

The second feature of this gearbox CM is the measurement of the lubricant pH to check the quality. Measured pH of lubricant indicates the amount of oil oxidation and removed additives. For this purpose, a sensor was made by two electrodes that work as the capacitor. In fact, oil is the electrolyte of this capacitor, and oil conductivity changes by pH value. This sensor is demonstrated in Fig. 7.

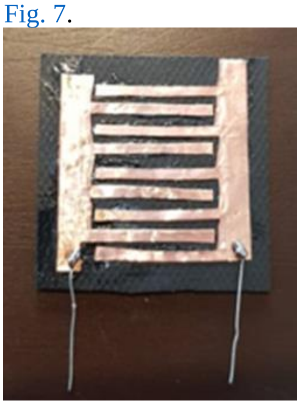

Fig. 7. fabricated capacitor for pH measuring of lubricant

Calibration of the pH sensor was occurred by comparing measured capacitance value with indicated by strips paper pH. Fig. 8 represents the correlation between the pH values and capacitance values. Table 1 illustrates the pH value and measured capacitance of lubricant.

TABLE I. MEASURED PH VALUES OF LUBRICANT AND CAPACITANCE OF THEM

Test number	C (Microfarad)	pH
1	16.69	2.4
2	17.19	2.5
3	17.22	2.9
4	14.57	3
5	20.20	9
6	594.10	12

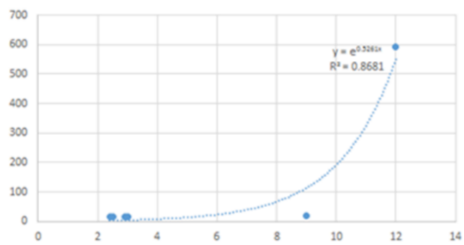

Fig. 8. The correlation between pH values and capacitance values

C. Measuring Temperature

The third part of this gearbox CM system measures the temperature of the lubricant, and it can alarm to remind the operator. Most of the gearboxes have a datasheet to show operation conditions such as temperature. If the oil temperature reaches the threshold, the alarm of the system will be active. An example of a gearbox label is revealed in Fig. 9.

Fig. 9. Operation label of gearbox

D. Evaluation of the System

For evaluating system accuracy in recognizing the fault type of the gearbox, the system is tested with a gearbox. In the case of normal gearbox testing with an angular velocity of 1.25 R/s, the vibration signal is reached and unveiled in Fig. 10. Then, an unbalance mass is appended at the end of the shaft as shown in Fig. 11. Moreover, bolt and nut of bearing stand were loosed to observe the effect of that in acceleration signal. This signal is shown in Fig. 12. Finally, misalignment of gears shaft was applied in the shaft, and the resulted signal is illustrated in Fig. 13. The acceleration signal by misalignment in the system shown in Fig. 14.

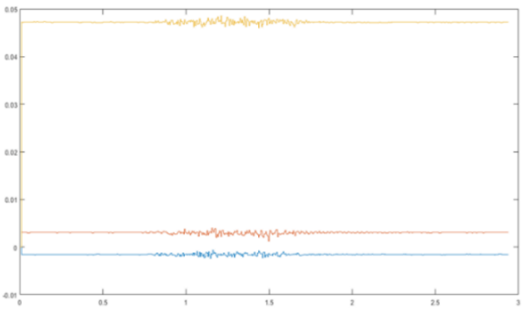

Fig. 10. The acceleration signal in the normal gearbox in X, Y, Z directs

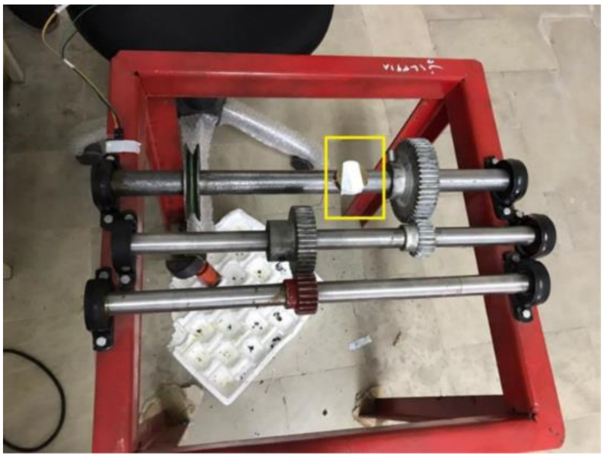

Fig. 11. Unbalance mass appended at the shaft

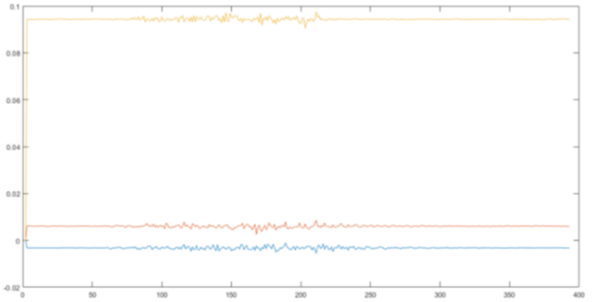

Fig. 12 The acceleration of system by unbalancing fault

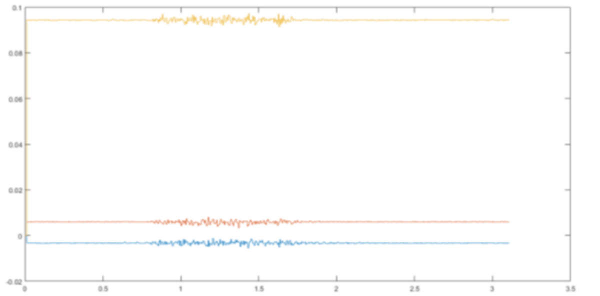

Fig. 13. The acceleration signal by created looseness in the base of bearing

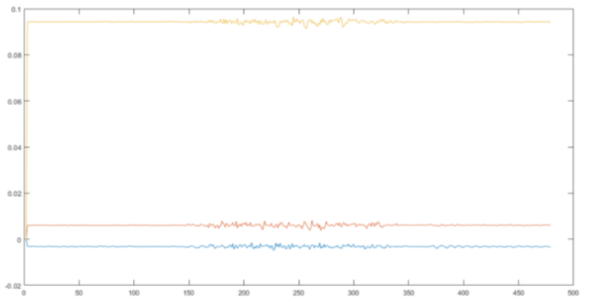

Fig. 14. The acceleration signal by misalignment in the system

III. Result and Discussion

After comparing the acceleration signal to the definite patterns by the proposed CM program, the compatibility of signals was obtained. For unbalance case, the goodness of fitting is presented in Fig. 15. Also, The FFT was used to convert time domain acceleration, $a(n)$, to frequency domain acceleration, $a(k)$, according to (2).

$$a(k) = \sum_{n=0}^{N-1} a(n) e^{-j2\pi kn/N} \quad (2)$$

$$k = 0, 1, 2, \dots, N-1$$

As can be seen, in Fig. 16 and Fig. 17, the acceleration amplitude of unbalance shaft is diminished, and the peak shifted.

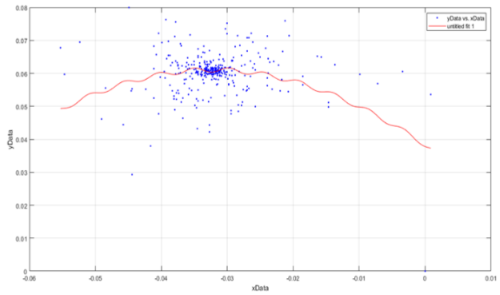

Fig. 15. The goodness of fitted signal to reference signal in case of unbalance mass

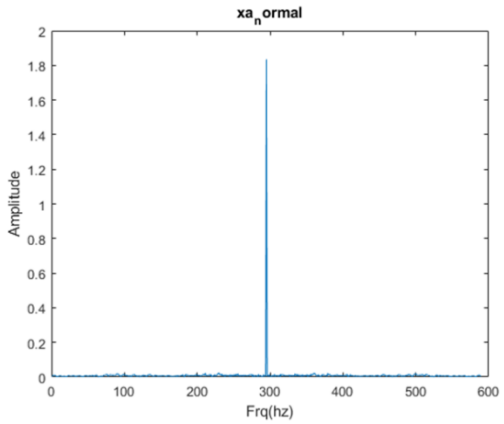

Fig. 16. The acceleration signal in the frequency domain in the normal shaft of the gearbox

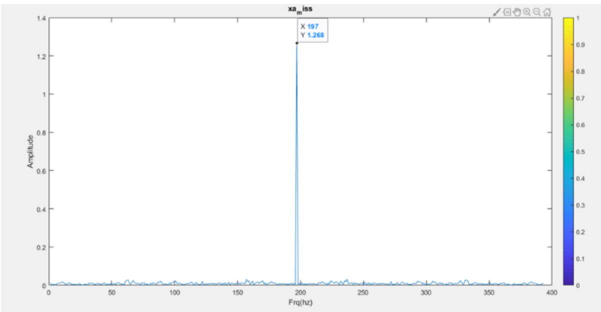

Fig. 17. The acceleration signal in the frequency domain in case of unbalance fault

In case of looseness in the bearing stand, the goodness of fitting curve to the reference pattern is acceptable (Fig. 18).

On the other hand, in the frequency domain, the amplitude of the signal is increased and can be seen in Fig. 19.

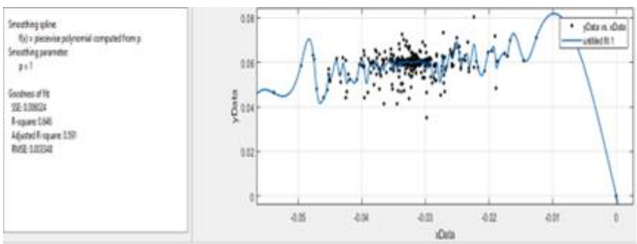

Fig. 18 The goodness of fitted signal to reference signal in case of looseness of bearing stand

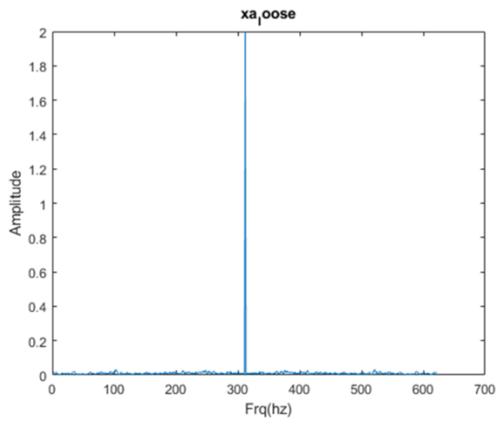

Fig. 19. The acceleration signal in the frequency domain by the looseness of bearing stand

Finally, the goodness of fitted curve to reference pattern is illustrated in Fig. 20 when misalignment has existed in the shaft. In this case, the compatibility is improved. Furthermore, in the frequency domain, the amplitude is decreased notably and presented in Fig. 21 while the peak is shifted to the lower frequency.

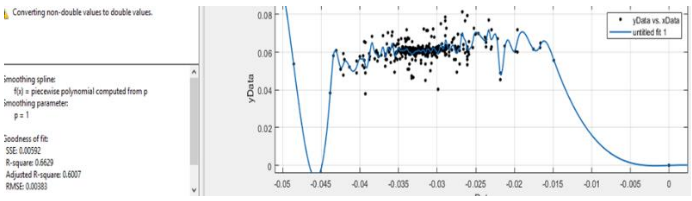

Fig. 20. The goodness of fitted signal to reference signal in case of misalignment of the shaft

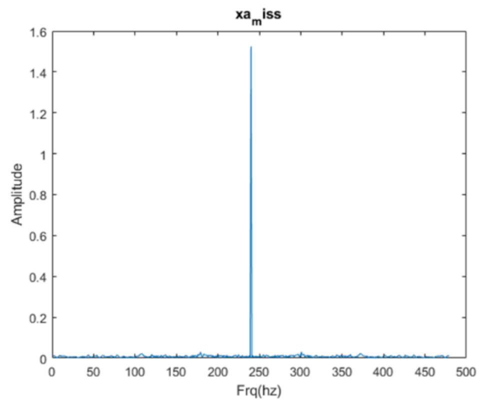

Fig. 21. The acceleration signal in the frequency domain by misalignment of shafts

IV. Conclusion

Having a CM system for gearboxes to indicate the quality and temperature of lubricant and its body vibration is more important to reduce the cost of repair and maintenance. The presented CM system in this paper shows that it can identify some failures in the gearbox such as bent shaft, unbalance mass, misalignment of shafts, looseness of bearing housing. In addition to this potential, the accuracy of the pH sensor is acceptable, and temperature sensor accuracy is proper to indicate of lubricant heating point.

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