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Inductive debris sensor using one energizing coil with multiple sensing coils for sensitivity improvement and high throughput

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ABSTRACT

Inductive oil debris monitoring has been widely used in the prognosis of machinery faults. This work proposes a new structure of inductive debris sensor that provides sensitive debris-sensing capability. This structure, which includes multiple sensing coils inside an energizing coil, considerably differs from traditional structures. Theoretical analysis shows that the proposed structure can significantly improve sensitivity. The sensor with two semicircular sensing coils is preliminarily designed and tested. The performance of the sensor is evaluated using a simple and efficient test platform. Experimental results show that the designed sensor can identify 120 μm (D) ferrous particles and 210 μm (D) non-ferrous particles in a pipe with an inner diameter of 34 mm.

1. Introduction

Modern industry demands enhanced reliability and efficiency in the performance of machines. Machine condition monitoring and fault detection technologies play important roles in maintaining and extending the health of rotating and reciprocating machineries used in various fields, including manufacturing, transportation, and military. These technologies are beneficial for the timely prevention of disastrous consequences resulting from the failure of key system components and unwanted production delays. Several condition monitoring methods are available to obtain the running state information of machines. These methods typically include vibration pattern, thermal analysis and acoustic emission. Although these methods have been widely adopted in many studies due to their inexpensive sensors and advanced techniques, oil condition monitoring provides a direct, efficient, and reliable approach for monitoring tribological performance in machine operation. Research has found that a direct relationship exists between the size of wear debris in oil and wear level in machinery components [1]. An online debris sensor that identifies abnormal particles in the lubricating oil of machines in real time has attracted the attention of researchers and sensor producers [2]. Efforts should be exerted to improve online techniques for the timely and accurate determination of the lubrication condition. Several online debris detection techniques, which can be mainly classified into optical [3,4], ultrasonic [5,6], capacitive [7–9], and electromagnetic [10–13] methods, have been developed. The electromagnetic method is selected for oil condition monitoring in the industrial market due to its simpler and lower-cost structure, more reliable performance, more complete wear debris information, and less sensitivity to interference, compared with other methods.

An inductive sensor that applies the electromagnetic method can obtain complete information about the size and material type of the wear debris. Ferromagnetic and nonferromagnetic particles, along with their size, can be differentiated by observing the phase and amplitude of the inductive signal. Several studies reported an inductive method for estimating the composition and size of metal particles. The amplitude of output voltage pulses due to the passage of a metal debris particle is proportional to the volume of the particle, but it is also approximately the inverse cube of coil diameter [14,15]. Thus, the minimum detectable particle size of an inductive debris sensor is associated with the diameter of the oil flow tube.

A variety of commercially available inductive debris sensors have been proposed in recent years. Various sensors possess the oil tubes of the different diameter. A large bore diameter can increase flow rate and reduce the probability of being clogged by large debris. However, a large bore diameter is not conducive to sensor's induction of small particles. Considering the bore diameter, the definition of parameter S will be given to conveniently compare sensitivity of various sensors. The sensitivity factor S is defined as $S = D_P/D_t$, where D_t is the diameter of the oil tube and D_P is the minimum size of detectable particles. S is almost a constant for sensors using the same techniques. Obviously, the smaller the parameter S, the better the level of sensors techniques. One of the most famous inductive sensors is MetalSCAN from the company GasTop. This product consists of two energizing coils and one sensing

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coil around a single oil channel [16]. Many studies have been conducted based on this sensor. However, the detection performance of this sensor is severely influenced by background noise and vibration interference. The product specifications of MetalSCAN indicate that its sensitivity to ferromagnetic and nonferromagnetic spherical particles is 100 μm and 405 μm, respectively, and its oil tube has approximately a bore diameter of 9.525 mm. For MetalSCAN, S is about 0.01. An inductive sensor for windmills, called TechAlert™ 10 [17], is produced by the company Macom. This sensor can detect ferrous debris with sizes between 50 μm and 100 μm, and nonferrous debris with sizes between 150 μm and 200 μm in an oil channel with an inner diameter of 4 mm. Hence, S is about 0.0125. Another commercial product, the Patrol In-Line Debris Sensor of MTML [18], consists of one reference coil and one sensing coil that are connected electrically in series. This sensor can detect individual metallic debris particles as small as 25 μm for ferrous particles and 90 μm for nonferrous particles in a pipe with an inner diameter of 5 mm. S is calculated to be 0.005. In addition to commercial products, there are considerable researches on inductive debris sensors. Du separately investigated a double-layer planar coil and a solenoid coil in terms of detecting metal debris [19]. A comparison indicated that the double-layer planar coil sensor obtained higher sensitivity and was able to measure ferrous and nonferrous particles with sizes ranging from 50 μm to 150 μm in a meso-scale fluidic pipe (an inner diameter of 1 mm), and S is about 0.05. Du also presented a parallel inductance-capacitance resonance method that amplifies impedance change caused by the passage of a debris particle. The detection limits for ferrous and nonferrous particles are 20 μm and 55 μm, respectively [20], and S is reduced to 0.02. The debris test results for the single- and three-coil configurations clearly showed the three-coil design demonstrated better sensitivity performance [21]. A simplified mathematical model and a finite element simulation model for a sensor can be established to optimize the structure of the sensor and investigate the influences of several key parameters, such as the coil turns and enwinding styles, on detection performance [22–24]. Ding et al. designed a novel structure for an inductive device that was constructed using a sensing coil sandwiched between two face-to-face planar field coils [25]. The device, which was integrated with a post-processing circuit, can detect 120 μm ferrous debris and 500 μm nonferrous particles for a pipeline with an inner diameter of 10 mm, where S is 0.012.

This paper proposes a new concept that multiple sensing coils can improve the sensitivity of the inductive debris sensor based on one energizing coil. Analysis shows that the structure can efficiently couple the exciting magnetic field with the sensing terminal. In order to verify it, a triple-coil wear debris sensor is preliminarily designed. The main structure includes an energizing coil and two semicircular sensing coils inside the energizing coil. A simple signal processing circuit is used in the experiment. The experiment results show that the sensor exhibits relatively high sensitivity, and its sensitivity factor S can reach approximately 0.003.

2. Principle of multiple sensing coils inside an energizing coil

The mechanical structure of the proposed sensor has two main parts, namely, the energizing coil and the sensing coils. In general, the three circular coils of common inductive debris sensors are placed side by side, with two sides being symmetrical, as shown in Fig. 1. The developed structure includes an energizing coil and multiple sensing coils. The sensing coils are arranged inside the energizing coil. To make full use of magnetic field, multiple sensing coils are designed, as shown in Fig. 2. The high currents flow through the energizing coil to produce strong magnetic flux density. The disturbance captured by the sensing coil due to the passage of a metallic particle is increased under the environment of strong magnetic field. Besides, every sensing coil only needs to connect one reference coil to obtain initial zero output voltage, and the sensing zones can work in parallel without loss of throughput. (The sensing coils with the segmented circular shapes are adopted to be conveniently analyzed and fabricated in the following contents.)

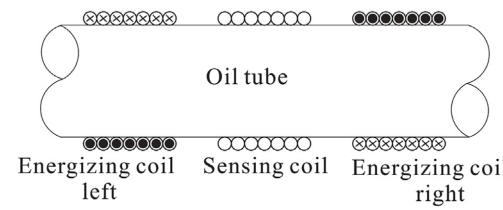

Fig. 1. Traditional structure of a triple-coil inductive debris sensor.

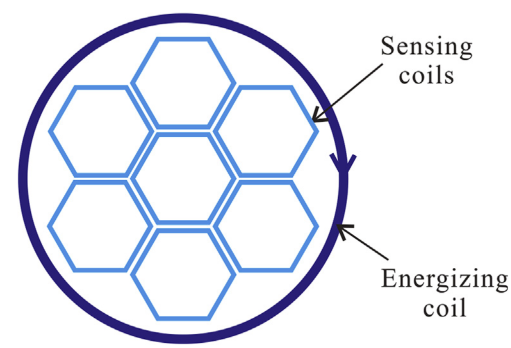

Fig. 2. The cross-sectional view of the proposed structure: an energizing coil and multiple sensing coils.

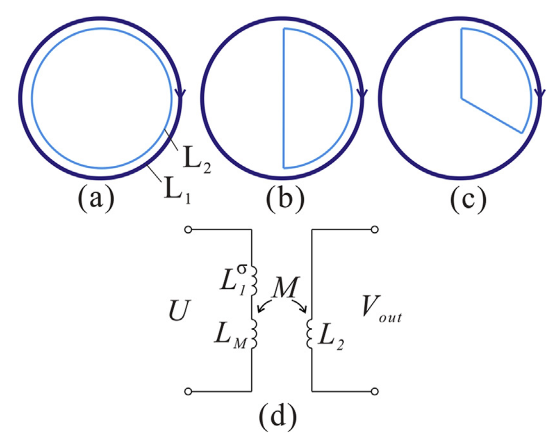

Fig. 3. Coupling between the energizing coil and the sensing coil with different segmented circular shapes. (a) Whole circular sensing coil, (b) semicircular sensing coil, (c) 1/3 circular sensing coil, and (d) an equivalent measurement circuit for an imperfectly coupled transformer.

To demonstrate the influence of this kind of sensing coil on the output signal, sensitivity analysis is conducted by establishing equivalent measurement circuits, as shown in Fig. 3. According to the working principle of the sensor, coupling between the energizing coil and the sensing coil can be regarded as an imperfectly coupled transformer. The sensing coils are designed as the structure of the segmented circle, which can be conveniently analyzed. The sensing coils have the same center as the energizing coil, and the magnetic field in every sensing coil is identical. Thus, the output voltage of one sensing coil induced by metallic particles is only considered. The primary circuit consists of the inductance L_1 of the energizing coil. The open-circuit self-inductance L_1 includes leakage inductance L_1^{σ} and magnetizing inductance L_M. An alternating voltage U is applied to the energizing coil. The secondary circuit of the open-circuit coil includes the inductance L_2 of the sensing coil. All the resistances of the coils are ignored. Fig. 3(a) shows the coupling between the circular energizing coil and the sensing coil. The magnetic flux produced by the energizing coil mostly passes through the sensing coil in the ideal case. Thus, we obtain