Sensitivity comparison of impedance sensors with different coil arrangements

Laihao Ma, Hongpeng Zhang*, Lin Zeng, Haotian Shi, Chenzhao Bai and Xupeng Zhao

Marine Engineering College, Dalian Maritime University, Dalian, China.

*Corresponding author e-mail: Zhppeter@163.com

Abstract. Two inductance-capacitance dual mode sensors based on different arrangement of dual coil and microchannel for oil multi-contaminant detection are proposed. The inductance detection model of metal particles and capacitance detection model of non-metal particles are constructed theoretically. The experimental results show that the two dual mode sensors both can realize inductance detection of iron and copper particles and capacitance detection of water droplets and air bubbles in oil. The detection sensitivity can be effectively improved by placing the microchannel on the edge of coil inner hole. The sensor of dual coils perpendicular to microchannel has more sensitive in inductance detection and the sensor of dual coils parallel to microchannel has more sensitive in capacitance detection. This research is helpful to improve the design and sensitivity of oil multi-contaminant detection sensor, and is of great significance to the realization of health monitoring and fault diagnosis of machinery.

1. Introduction

Contaminants in oil contain abundant information about the health status for machinery, among which the type, size and shape of metal particles in oil can characterize the wear location, wear rate and wear degree of mechanical equipment, the water in oil would aggravate the emulsification process of oil and cause the corrosion of friction pairs, the air in oil would create cavitation and cause abnormal vibration of mechanical equipment[1-3]. So detecting oil contaminants is a direct and reliable approach to monitor the health conditions of machinery and to provide important decision-making basis for fault diagnosis.

For oil contaminants detection, several online sensors based on optical scattering [4,5], acoustic emission [6,7], capacitance sensing [8-9], and inductive sensing [10-12] have been developed. All of these sensors have many advantages and also certain limitations, among them, the optical sensor can detect very small particles due to its high sensitivity, but cannot distinguish the metal particles properties and it is easily susceptible to the oil clarity[13]; the acoustic sensor is vulnerable to the vibration of mechanical equipment, and the detection accuracy is low[14]; the capacitive sensor can distinguish droplets and bubbles by different dielectric constants, but is unable to distinguish the types of metal particles and the detection accuracy would be affected by the deterioration of oil[15]; the current inductive sensor using 3-D solenoid has a low sensitivity, which can only detect debris larger than 100 µm[16]. However, the wear debris less than 100µm, typically in the range of 50–100 µm, have indicated abnormal wear conditions for machinery[17], in order to improve the inductance detection sensitivity, Li D et al.[18] proposed an inductive pulse sensor with 20-turn planar coil, which is capable of detecting...
ferrous debris of 32 µm in a 1.2mm fluidic pipe; Zhu et al. [19] developed a high-sensitivity wear debris sensor with two planar coils adding a pair of ferrite cores, which can detect 11µm ferrous debris in 1mm diameter fluidic pipes; Zhang H et al.[20] proposed a microchannel structure that can decrease the distance between wear particles and the inner wall of the coil, which is able to detect 10µm debris in a 230µm diameter fluidic pipe. Nevertheless, various sensors developed above can only detect ferromagnetic and non-ferromagnetic particles, but cannot detect non-metallic particles in oil, such as water droplets and bubbles.

The proposed dual coil structure can realize the differential detection of multi-pollutants including iron particles, copper particles, water drops and bubbles in the oil, which cannot be achieved by a single coil structure. Based on the previous work, the microchannel placed on the edge of dual coil inner hole can (1) improve detection sensitivity, (2) eliminate the multi peak phenomenon caused by detection of a single particle, which is helpful for particle counting [3].

2. Inductance-capacitance dual mode sensor

2.1. Sensor structure
The design of two inductance-capacitance dual mode sensors is shown in Fig.1. The dual mode sensors are composed of a straight microchannel and two identical dual coils. The diameter of microchannel D1 is 500µm. The diameter of coil wire core D2 is 70 µm (an insulating paint with a thickness of 10 µm covered the core) and the diameter of coil inner hole D3 is 900µm. For the sensor of dual coils perpendicular to microchannel, the dual coils are fastened together, as the radial distribution of magnetic induction intensity in planar coil is not uniform, i.e., the magnetic induction intensity in coil inner wall is greater than that in the center of coil, we placed the microchannel in the inner wall not the center of coil to obtain higher detection sensitivity. For the sensor of dual coils parallel to microchannel, the dual coils are on both sides of microchannel and the microchannel is near the outer edge of inner wall of dual coil, which can ensure that the sensing zone is in the area where the magnetic induction intensity of the coils is the largest and eliminate the multi peak phenomenon caused by detection of a single particle.

![Fig. 1 Design of the dual mode sensors.](image)

2.2. Inductance detection mode
When the coil is applied with an alternating current, the alternating magnetic field will be generated inside coil. Metal particles are magnetized in alternating magnetic field and generate eddy currents. When a ferromagnetic metal particle passes through the sensing zone, it’s relative permeability is higher, which makes the magnetization effect greater than the eddy current effect and has an enhanced effect
on the original magnetic field, and then coil equivalent inductance increases. When a non-ferromagnetic particle passes through the sensing zone, the eddy current plays a dominant role, which weakens the original magnetic field, and then coil equivalent inductance decreases. Therefore, the ferromagnetic metal particles and non-ferromagnetic metal particles can be distinguished by the direction of inductance signal, and the size can be determined by the height of inductance signal.

![Fig.2 Schematic diagram of inductance detection mode: (a) dual coils perpendicular to microchannel; (b) dual coils parallel to microchannel.](image)

2.3. Capacitance detection mode
When dual coils are connected to the positive and negative ends of power supply respectively, the dual coils can be regarded as two plates as shown in Fig.3, which could be equivalent to a ring capacitor.

![Fig.3 Schematic diagram of capacitance detection mode: (a) dual coils perpendicular to microchannel; (b) dual coils parallel to microchannel.](image)

We can see that the capacitance variation of the two sensors is related to the relative permittivity and the volume of particles when the sensor sizes and the parameters of alternating current are determinate. As the relative permittivity of air (about 1) is less than the relative permittivity of oil (about 2.6), and the relative permittivity of water (about 80) is greater than the relative permittivity of oil, so the output capacitance will generate a downward and upward pulse signal for detecting air bubbles and water droplets, separately.

3. Sensor fabrication and experimental preparation

3.1. Inductance detection results and discussion
Connect the lead wires of dual coils according to inductance detection mode and the partial detection signal is extracted as shown in Fig.4. It is easy to find that the inductance amplitudes of detecting iron particles and copper particles by the dual coils perpendicular to microchannel are higher than the amplitudes of the dual coils parallel to microchannel. To quantify and compare the detected signals, the
signal amplitude, noise and SNR are selected as evaluation indexes, and the statistical results are shown in Tab.1.

![Inductance detection results of iron particles and copper particles. (a) iron particles ranging from 70 to 75µm in size, (b) copper particles ranging from 135 to 140µm in size.](image)

**Fig.4** Inductance detection results of iron particles and copper particles. (a) iron particles ranging from 70 to 75µm in size, (b) copper particles ranging from 135 to 140µm in size.

| Particle Size          | Sensor Type                        | Inductance Amplitude /F | Average Noise /F | SNR |
|------------------------|------------------------------------|-------------------------|------------------|-----|
| 70-75µm iron particle  | Dual coils perpendicular to micro-channel | 4.04×10^9              | 3.14×10^10       | 12.9|
|                        | Dual coils parallel to micro-channel | 1.62×10^9               | 3.09×10^10       | 4.6 |
| 135-140µm copper particle | Dual coils perpendicular to micro-channel | 5.23×10^10             | 2.04×10^10       | 2.6 |
|                        | Dual coils parallel to micro-channel | 3.72×10^10             | 2.08×10^10       | 1.8 |

For the detection of the same particles, the noise of the two sensors is basically the same, but the inductance amplitude and SNR of dual coils perpendicular to microchannel are about 2.5 times higher than those of dual coils parallel to microchannel when detecting 70-75µm iron particles, and about 1.4 times of dual coils parallel to microchannel when detecting 135-140µm copper particles. This is mainly due to the difference of magnetic field intensity between the two sensor detection areas. For the dual coils perpendicular to microchannel, the dual coils are close to each other. The dual coils parallel to microchannel are separated by 500µm microchannel. Therefore, the magnetic induction intensity in the detection area of dual coils perpendicular to microchannel is larger, and so the magnetization intensity of particles is also higher.

3.2. Capacitance detection results and discussion

Connect the lead wires of dual coil according to the capacitance detection mode, the detection results of 250-260µm water droplets using dual coils perpendicular to microchannel and dual coils parallel to microchannel are shown in Fig.5(a) and (b), respectively. Fig5(c) shows the detection results of 450-460µm air bubbles using dual coils perpendicular to microchannel. Fig.5(d) shows the detection results of 300-310µm air bubbles using dual coils parallel to microchannel. Similar to the comparison analysis of inductance detection, the statistical results of capacitance amplitude, average noise, and SNR are also shown in Tab. 2.
theoretical analysis was verified by experiments. This work compared the sensitivity of two dual mode sensors according to different position of dual coils and microchannel in the paper. The detection sensitivity can be effectively improved by placing the microchannel on the edge of coil inner hole. For the dual coils perpendicular to microchannel, the dual coils close to each other make the magnetic induction intensity in the detection area higher than that of dual coils parallel to microchannel, so the sensitivity of inductance detection was better than that of dual coils parallel to microchannel. For the dual coils parallel to microchannel, the electric field intensity of the equivalent capacitor was more uniform, which makes the capacitance detection sensitivity of dual coils parallel to microchannel higher than that of dual coils perpendicular to microchannel. The theoretical analysis was verified by experiments. This work compared the sensitivity of two dual mode sensors according to different position of dual coils and microchannel in the paper.
sensors comprehensively, which can provide support for next step to improve the design of dual mode sensor, and is of great significance for the health status monitoring of machinery.

Acknowledgments
This work was financially supported by the Innovative Talents Training Project for the Doctoral Students of Dalian Maritime University (Grant No.: BSCXXM005).

References
[1] Ren Y, Li W, Zhao G. Inductive debris sensor using one energizing coil with multiple sensing coils for sensitivity improvement and high throughput. Tribology International, 2018, 128, 96-103.
[2] Feng S, Yang L, Qiu G. An Inductive Debris Sensor Based on a High-Gradient Magnetic. IEEE Sensors Journal, 2019,19, 2879-2886.
[3] Ma L, Xu Z, Zhang H. Multifunctional Detection Sensor and Sensitivity Improvement of a Double Solenoid Coil Sensor. Micromachines, 2019,10,377.
[4] Gauglitz G. Direct optical sensors: principles and selected applications. Analytical & Bioanalytical Chemistry, 2005, 381,141-155.
[5] Oehme I, Wolfbeis O S. Optical Sensors for Determination of Heavy Metal Ions. Microchimica Acta,1997, 126, 177-192.
[6] Feng G, Tsai M, Jeng Y.A micromachined, high signal-to-noise ratio, acoustic emission sensor and its application to monitor dynamic wear. Sensors and Actuators A (Physical), 2012, 188, 56-65.
[7] Tokitou K, Shida K The Discrimination Between Water and Oil Using Ultrasonic Sensor. Ieej Transactions on Sensors & Micromachines,2004,124, 415-420.
[8] Demori M, Ferrari V, Strazza D. A capacitive sensor system for the analysis of two-phase flows of oil and conductive water. Sensors and Actuators: A Physical,2010, 163, 172-179.
[9] Zubair M, Tang T. A High Resolution Capacitive Sensing System for the Measurement of Water Content in Crude Oil. Sensors,2014,14, 11351-11361.
[10] Flanagan J, Jordan J, Whittington H. Wear-debris detection and analysis techniques for lubricant-based condition monitoring. Journal of Physics E Scientific Instruments, 1988, 21,1011.
[11] Fan H, Zhang Y, Ren G. Experimental Study of an On-line Monitoring Sensor for Wear Particles in Oil. Tribology, 2010, 30, 338-343.
[12] Yan H, Zhang Y. The Design of an On-line Monitoring Sensor of Wear Mental Particals and the Analysis of Its Characteristic. Journal of Trasduction Technology, 2002, 4, 333-338.
[13] Li D, Jiang Z An integrated ultrasonic–inductive pulse sensor for wear debris detection. Smart Materials & Structures, 2017,22, 025003.
[14] Murali S, Jagtiani A, Xia X. A microfluidic Coulter counting device for metal wear detection in lubrication oil. Review of Scientific Instruments, 2009, 80, 1011.
[15] Hong W, Cai W, Wang S, Mileta M. Mechanical wear debris feature, detection, and diagnosis: A review. Chinese Journal of Aeronautics, 2018,31, 867–882.
[16] Li D, Jiang Z. On-Line Wear Debris Detection in Lubricating Oil for Condition Based Health Monitoring of Rotary Machinery. Recent Patents on Electrical Engineering,2011, 4, 1-9.
[17] Shi H, Zhang H, Ma L, Zeng L. A multi-function sensor for online detection of contaminants in hydraulic oil. Tribology International, 2019, 138 196-203.
[18] Li D, Jiang Z. A high throughput inductive pulse sensor for online oil debris monitoring. Tribology International,2011, 44,175-179.
[19] Zhu X, Li D, Jiang Z. A 3×3 wear debris sensor array for real time lubricant oil conditioning monitoring using synchronized sampling. Mechanical Systems and Signal Processing, 2017, 83, 296- 304.
[20] Wu Y, Zhang H, Zeng L. Determination of Metal Particles in Oil using a Microfluidic Chip-Based Inductive Sensor. Instrumentation Science & Technology, 2015, 44, 259-269.