Experimental research on coil turns to double coil multi-parameter impedance sensor

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Abstract: In this study, the detection principle of the dual-coil multi-parameter impedance detection sensor is introduced, and the influence of the number of coil turns on the experimental results is studied. The author produces a series of dual-coil multi-parameter impedance detection sensors and builds an experimental detection platform. The test parameters are compared and analysed under different coil turns. The experimental results show that for the detection of inductive or capacitive parameters of the same pollutant detection particle, the amplitude of the inductance or capacitance parameter increases with the increase of the number of turns of the coil, and the signal-to-noise ratio also increases with the increase of the number of turns of the coil. Therefore, increasing the number of turns in the micro-plane coil helps improve the detection accuracy and signal-to-noise ratio of the impedance sensor. The results of the study show that the dual-coil multi-parameter impedance detection sensor can realise the identification and detection of pollutant particles, and it has certain practical significance for the new multi-parameter on-line oil differential detection.

1 Introduction

Oil is the blood of a mechanical system. It is not only the working medium that transfers energy, but also play a role in reducing the friction between the mechanical components, cooling hydraulic components, reducing the temperature rise of the hydraulic system, controlling the surface oxidation of the hydraulic components, extending the service life of the equipment, reducing mechanical equipment vibration \cite{1, 2}. According to statistical data, 75\% of system failures are caused by oil pollution \cite{3–6}. Major pollutants include solid particulate pollutants, air, water, and harmful chemicals. The solid particulate contaminants in the oil include non-metallic impurities (such as gravel, coke, and asphalt) and metallic particulate contaminants. It mainly comes from particles such as dust that come in from the outside world (during operation and maintenance) and mental particles that are generated due to friction during the operation of mechanical equipment. Also the latter is the main source of system failure. Water, air, and other invasive impurities in the oil mainly come from the production, transportation, and system installation of the oil. The presence of water, air and heat energy generated during the operation of machinery and equipment in the oil are the root cause of loss of oil consumption and oxidative deterioration. In addition, the particles in the oil act as catalysts to catalytically oxidise the oil and aggravate the deterioration of the oil. In short, solid particle contaminants can wear mechanical equipment, air and water can accelerate the oxidation and hydrolysis of oil, and in the process it may produce some chemical pollutants \cite{7, 8}. For example, once the solid particles block the orifices, the components will not work properly, and the valve elements of some valve parts may be worn out, stuck or moved. The oil is heated above 20°C to produce acids, hydrocarbons and sediments. Oil and oxygen are oxidised above 160°C to form acid and oxide residues. The oil and water are hydrolysed above 90°C to produce acids, alcohols, and emulsions \cite{9, 10}.

2 Detection principle

In this experiment, an opposed micro-plane coil multi-parameter impedance detection sensor is used. The sensor mainly consists of two single-layer micro-plane inductive coils, direct microfluidic channels, inlet and outlet of flow channels, and coil connectors. The two single-layer micro-plane inductive coils are placed in close proximity to each other on both sides of the flow channel. The straight microfluidic channels pass through the edges of the two single-layer planar inductor coils. The role of this part is to detect contaminant particles and transmit detection signals. By changing the connection of the two micro-plane inductance coils, the impedance sensor can simultaneously detect changes in the oil’s inductance parameters, resistance parameters, and capacitance parameters without the need to replace the detection chip. Fig. 1 shows the structure of a multi-parameter impedance sensor with opposing micro-plane coils.

2.1 Inductance detection principle

When the impedance sensor detects the inductance parameters, two micro-plane coils are connected in parallel in the same direction, and a high-frequency AC excitation voltage is applied at both ends of the micro-plane coil, as shown in Fig. 2. When using parallel connection in the same direction, the equivalent inductance $L_{eq}$ of the inductor is

$$L_{eq} = \frac{L_1L_2 - M^2}{L_1 + L_2 - 2M} \quad (1)$$

At this point, two micro-plane coils generate alternating magnetic fields in the same direction. In addition to the self-inductance $L$ caused by the self-current of each micro-plane coil, the mutual inductance $M$ caused by the two micro-plane coils. At
the ferromagnetic metal particles passes through the detection area, an upward pulse of the inductance signal is generated.

2.2 Capacitance detection principle

When the impedance sensor performs capacitance parameter detection, the two single-layer planar coils can be equivalent to two electrode plates of a circular-ring parallel capacitor, and high-frequency AC excitation voltages are applied across the electrodes, as shown in Fig. 3.

The following is a theoretical analysis of the electric field distribution of a circular-ring parallel capacitor. Under the condition of ignoring the edge effect of a capacitor plate, an appropriate stable voltage is applied to both ends of the two electrodes. The size of the impedance sensor capacitance is related to the dielectric constant of the dielectric between the electrodes. When no particles pass through between the plates filled with the detection fluid, the capacitance of the detection system is maintained at a fixed value. When there is a detection particle passing between the plates filled with the detection fluid, the dielectric constant of the sensor detection area will change due to the difference in the dielectric constant between the detection particles and the oil in the fluid. As a result, the capacitance of the capacitor formed by the micro-plane coil changes, causing a corresponding pulse in the capacitance parameter of the detection system. Therefore, non-metal contaminant particles (such as bubbles and water) can be distinguished by detecting the positive and negative capacitance pulse parameters of the coil.

The relative permittivity of air is 1, the relative permittivity of oil is 2.6, and the relative permittivity of water is 80. Therefore, when the oil mixed with air bubbles passes through the detection area, the dielectric constant of the air bubbles is smaller than that of the hydraulic oil, so that the equivalent capacitance of the double coil is reduced. When the oil mixed with water passes through the detection area, the dielectric constant of the water is larger than that of the hydraulic oil, which increases the equivalent capacitance of the double coil. Therefore, when the oil mixed with air bubbles passes through the detection area, a downward capacitive pulse signal is generated. When the oil mixed with water droplets passes through the detection area, an upward capacitive pulse signal is generated. The capacitance detection of the multi-parameter impedance sensor of the opposite micro-plane coil is based on the principle that the difference in the dielectric constant between the air bubble and the water, and then causes the change of the capacitance parameter of the micro-plane coil. The bubble and water are distinguished by detecting the positive and negative capacitance pulse signals of the coil. The size and number of changes in capacitance parameters.

3 Experiment

3.1 Production of the chip

The production of double-coil multi-parameter sensors includes the fabrication of single-layer coils, the soldering of joints, the configuration, casting and curing of polydimethylsiloxane (PDMS) [13, 14], the final shaping and inspection of the chip [15]. A set of multi-parameter impedance sensors with different number of turns is fabricated for experiments. The number of the micro-plane coil turns is 20, 30, 40, 50, and 60, respectively. The diameter of the micro-channels is uniformly 300 μm, and the coil diameter is unified to 70 μm. Fig. 4 shows the production process of a dual-coil multi-parameter sensor.

3.2 Experimental system of the multi-parameter sensor

When detecting pollutant particles, a multi-parameter detection system needs to be built, as shown in Fig. 5. The detection system consists of a dual coil multi-parameter sensor, an impedance analyser, a micro-injection pump, a microscope, and a computer. The test oil sample mixed with appropriate amount of metal particles, bubbles and water are put into a syringe, respectively, and the syringe pump is used to control the syringe and push the oil.
into the sensor. At a certain frequency and voltage, the impedance analyser is connected to the two connectors of the sensor. The inductance and capacitance parameters between the two joints are measured and transmitted to the computer, respectively.

4 Experimental results and analysis

4.1 Inductance detection

Firstly weigh the appropriate amount of 120–130 μm iron particles, then add the appropriate amount of hydraulic oil and mix it until ready. Finally, connect each part according to the detection system diagram, and control the syringe pump so that the detection fluid passes through the detection area of the chip. The excitation frequency of the impedance analyser is 2 MHz, the excitation voltage is 2 V, and the speed of the micro-injection pump is 0.03 mL/min. The iron particles pass through five kinds of sensors with different numbers of coil turns, and through the experimental data is obtained. When the number of micro-plane coil turns is different, the iron particles cause the magnitude of the inductance variation of the micro-plane inductance coil. Fig. 6 is a pulse diagram of the change of the inductance parameter when 120–130 μm iron particles pass through the detection area of the impedance sensor having 30 turns of the coil. It can be seen from the figure that the pulses generated by the iron particles are positive. Each forward pulse represents an iron particle. The amplitude of the pulse indicates the size of the iron particle.

When the number of micro-plane coil turns is different, the relationship between the amplitude inductance, the signal-to-noise ratio of the 120–130 μm iron particle and the coil turns is plotted, as shown in Figs. 7 and 8.

It can be seen from the figure that when the other parameters of the impedance sensor are fixed, the iron particles pass through the impedance sensor detection area, and the detected inductance parameter amplitude increases with the increase of the number of the micro-plane coil turns. At the same time, the signal-to-noise ratio of the inductance parameter also increases. The more the number of the micro-plane coil turns, the greater the magnetic field strength of the micro-plane coil and the larger the magnitude of the inductance caused by the iron particles passing through the detection area. Therefore, the ability of the inductance sensor's inductance parameter detection increases with the number of the micro-plane coil turns. Therefore, selecting an impedance sensor with a large number of the micro-plane coil turns can not only improve the detection accuracy of the sensor inductance parameter, but also improve the signal-to-noise ratio of the inductance parameter.

4.2 Capacitance detection

4.2.1 Bubble capacitance detection: Firstly, take the right amount of air, and then add the right amount of hydraulic oil and mix it. Finally, connect each part according to the detection system diagram, and use a syringe pump to control the detection area where 290–300 μm bubbles are mixed through the chip. The excitation frequency of the impedance analyser is 1 MHz, the excitation voltage is 2 V, and the speed of the micro-injection pump is 0.03 mL/min. The bubbles pass through five kinds of sensors with different numbers of turns, and through the experimental data obtained, the amplitude of the capacitance parameters of the micro-plane inductance coil caused by the different number of micro-plane turns is obtained. Fig. 9 shows the pulse diagram of the 290–300 μm bubbles that cause the change of the capacitance parameter when passing through the detection area of the impedance sensor of the coil with 50 turns. As can be seen from the figure, the pulses generated by the bubble are negative, and each negative pulse represents a bubble. The amplitude of the pulse indicates the size of the bubble.

When the number of the micro-plane coil turns is different, the relationship between the variation amplitude, the signal-to-noise ratio of the 290–300 μm bubble and the coil turns is plotted, as shown in Figs. 10 and 11.

As can be seen from the figure, when the other parameters of the impedance sensor are constant, the air bubble passes through
the detection area of the impedance sensor, and the detected capacitance amplitude increases as the number of the micro-plane coil turns increases. At the same time, the signal-to-noise ratio of the capacitance parameter also increases. The greater the number of the micro-plane coil turns, the greater the capacitance of the two ring-shaped capacitor plates equivalently formed by opposing micro-plane coils, and the larger the capacitance amplitude caused by bubbles passing through the detection area. Therefore, when the bubble is detected, the capacitance parameter detection capability of the impedance sensor increases as the number of the micro-plane coil turns increases. Therefore, selecting an impedance sensor with a larger number of the micro-plane coil turns not only improve the detection accuracy of the sensor capacitance parameter, but also improve the signal-to-noise ratio of the capacitance parameter.

4.2.2 Water capacitance detection: Firstly, take the appropriate amount of pure water, then add the appropriate amount of hydraulic oil and mix it. Finally, connect each part according to the detection system diagram, and use a syringe pump to control the 290–300 μm water droplets passing through the detection area of the chip. The excitation frequency of the impedance analyser is 1 MHz, the excitation voltage is 2 V, and the speed of the micro-injection pump is 0.03 mL/min. The water droplets pass through five kinds of sensors with different numbers of turns of the coil, and through the experimental data obtained, the magnitude of the change of the capacitance parameter of the micro-plane inductance coil caused by the drop of the micro-plane coils is obtained. Fig. 12 shows the pulse diagram of the 290–300 μm water droplets when they pass through the detection area of the impedance sensor with 50 turns of the coil. It can be seen from the figure that the pulses generated by the water droplets are positive. Each positive pulse represents a water droplet. The amplitude of the pulse represents the size of the water droplet.

When the number of the micro-plane coil turns is different, the relationship between the variation amplitude, the signal-to-noise ratio of the 290–300 μm water droplets and the coil turns is plotted, as shown in Figs. 13 and 14.

As can be seen from the figure, when the other parameters of the impedance sensor are constant, the water droplet passes through the detection area of the impedance sensor, and the detected capacitance amplitude increases as the number of the
micro-plane coil turns increases. The greater the number of the micro-plane coil turns, the greater the capacitance of the two ring-shaped capacitor plates equivalently formed by the opposing micro-plane coils, and the greater the capacitance amplitude caused by water droplets passing through the detection area. Therefore, when the water droplet is detected, the capacitance parameter detection capability of the impedance sensor increases as the number of the micro-plane coil turns increases. Therefore, by selecting an impedance sensor with a large number of the micro-plane coil turns, the detection accuracy of the sensor capacitance parameter can be improved.

5 Conclusion

The conclusions obtained through experiments in this paper are as follows: (i) When the contaminant particle inductance parameter is detected by an opposed micro-plane coil multi-parameter impedance detection sensor, the inductance amplitude of the impedance sensor increases with the increase of the micro-plane coil turns. At the same time, the signal-to-noise ratio of the inductor parameters also increases with the increase of the micro-plane coil turns. (ii) For the capacitance parameter detection of water droplets and bubbles, the capacitance amplitude when passing through the sensor also increases with the number of micro-plane coil turns. At the same time, the signal-to-noise ratio of the capacitance parameter also increases with the increase of the micro-plane coil turns.

Therefore, when the oil contaminant particles are detected, the detection accuracy of the impedance sensor can be improved and the noise can be reduced by increasing the number of micro-plane coil turns. In the course of future research, experiments can be conducted on other influencing factors.

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7 References

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