Analysis of Operation Characteristics of Inductance Sensor

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Abstract. Inductance sensor is widely applied in engineering survey. The operation principle of the inductance sensor has analyzed in this paper, the output characteristic function of the inductance sensor obtained by comparing the change relationship which coil inductance value displace with magnetic core when inductance sensor working. The simulation software has used to analyze an inductance sensor, and experiment has been taken to proof that, out linearity of the sensor is better within a certain measuring range, it is less than 0.8% in the 2mm working range, with the measuring range increases, the linearity of the inductance sensor become worse, and then affect the measurement accuracy. this research provides a basis for how to select the appropriate working range when using inductance sensors.

1. Introduction
Inductance sensor has been widely used in the engineering field due to its simple structure, reliable operation and high measurement accuracy [1]. Ideally, the input and output of sensor should have a good characteristic relationship; and the type is linear characteristic [2].

Inductance sensor usually presents a linear relationship, but due to the operating characteristic of the inductance sensor and it causes the inductance sensor cannot guarantee better linear output characteristic [3]. This paper mainly studies the relationship between the linear output characteristic of inductance sensor and the measurement range of the sensor, through analysis and experiment, it is proved that with the increase of the measurement range of the inductance sensor, the linear output characteristic of the sensor becomes worse, and then affect the measurement accuracy of the sensor. When selecting inductance sensor for engineering and technical personnel, the measurement requirement is integrated, and provides a basis for how to improve the measurement accuracy under the condition that the measurement range is met.

2. Analysis of Operation Principle of Inductance Sensor
The stable current produces can constant magnetic field. In the infinite vacuum, when the current distribution is known, the magnetic induction intensity at any point in the magnetic field can be calculated in Biot-Savart Law [4].

\[
B(P) = \frac{\mu_0}{4\pi} \int_{V} \frac{J(Q) \times R^2}{R^2} dV(Q)
\]

(1)
In Formula (1), \(dV(Q)\) represents the volume element around the source point \(Q\), the current density of this source point is \(J(Q)\); \(R\) is the distance from the source point \(Q\) to the field point \(P\), \(R^\circ\) is the unit vector from the source point \(Q\) to the field point \(P\); \(\mu\) is the vacuum permeability; \(V\) is distribution area of the current density.

The structure of the single solenoid coil inductance sensor is shown in Figure 1; the single solenoid coil can be regarded as a superposition of limited number of loop coils, formula (1) are integrated, the magnetic field distribution of the solenoid coil in the axial direction can be obtained.

\[
B(x) = \frac{\mu_0 NI}{2l} \left[ \frac{x + l/2}{\sqrt{r^2 + (x + l/2)^2}} - \frac{x - l/2}{\sqrt{r^2 + (x - l/2)^2}} \right]
\]  

(2)

Figure 2 is the distribution diagram of axial magnetic field intensity of solenoid coil, it is seen from the figure that the axial magnetic field intensity in the solenoid is an uneven magnetic field, and the distribution curve of magnetic field intensity is symmetric with the center of the dot \(O\), and the magnetic field intensity change in the vicinity which distance from dot \(O\) to \(\pm0.3l\) is relatively gentle in the axial direction, the magnetic field intensity which exceed \(\pm0.3l\) decreases sharply.
The inductance value of the hollow inductance coil is:

\[ L_0 = \frac{\psi}{I} = \frac{N\phi}{I} = \frac{NB_0\pi r^2}{I} \]  

If the magnetic core is inserted into the hollow inductance coil, the length of the magnetic core is \( l_c \), the diameter is \( 2r_c \), and the magnetic permeability of the magnetic core material is \( \mu_m \). Then the inductance coil will generate additional inductance under the action of the magnetic core, and its inductance value is:

\[ L_c = \frac{(\mu_m - 1)NB_0\pi r_c^2}{I} \]  

\[ L = L_0 + L_c = \frac{\mu_0 N^2 \pi}{I^2} \left[ r_c^2 \left( \sqrt{r_c^2 + l_c^2} - r_c \right) + (\mu_m - 1) r_c^2 \left( \sqrt{r_c^2 + l_c^2} - r_c \right) \right] \]  

\[ \Delta L = \frac{\mu_0 N^2 \pi (\mu_m - 1) r_c^2}{I^2} \frac{l_c}{\sqrt{r_c^2 + l_c^2}} \Delta l_c \]  

Because the internal magnetic field of the inductance coil is not uniform, the total inductance value of the inductance coil can be obtained by integrating the formula (1) into the range:

\[ L = L_0 + L_c = \frac{\mu_0 N^2 \pi}{I^2} \left[ r_c^2 \left( \sqrt{r_c^2 + l_c^2} - r_c \right) + (\mu_m - 1) r_c^2 \left( \sqrt{r_c^2 + l_c^2} - r_c \right) \right] \]  

\[ \Delta L = \frac{\mu_0 N^2 \pi (\mu_m - 1) r_c^2}{I^2} \frac{l_c}{\sqrt{r_c^2 + l_c^2}} \Delta l_c \]  

It can be known from formula (6) that the variation of inductance coil \( \Delta L \) and magnetic core displacement is proportional relationship; its scale factor is determined by space permeability \( \mu_0 \), coil turn \( N \), length of coil \( l \), magnetic conductivity of magnetic core \( \mu_m \), length of magnetic core, radius \( r_c \). But the two do not show a linear relationship when sensors in the actual working process, this is because, as the magnetic core moves in the coil, the length \( l_c \) of the magnetic core in the coil is not a
constant value, it will change with the working situation, therefore, the sensor presents certain nonlinearity during the working process.

3. Simulation of Inductance Sensor
In order to study the nonlinear influence relation of the magnetic core movement on the output of the inductance coil during the working process, the simulation software is used for analysis [5]. First, the three-dimensional simulation model of the inductance coil and the magnetic core is established, an inductance sensor as chief source, the size of the inductance coil and the magnetic core is determined, the internal diameter of the inductance coil is 1.8mm, the external diameter is 3.8 mm, the coil length is 9 mm, and the solid core radius is 0.8 mm, the magnetic core length is 9.4 mm and the core inserts 4.7 mm. The relationship between the inductance value and the magnetic core displacement is obtained by simulating the inductance value of the inductance coil when the magnetic cores in different positions, the simulation results are shown in Table 1.

| magnetic core displacement (mm) | coil inductance value L (mH) | change value of coil inductance ΔL (mH) |
|---------------------------------|-----------------------------|---------------------------------------|
| 0                              | 1.206986                    | 0                                     |
| 0.1                            | 1.224384                    | 0.017398                              |
| 0.2                            | 1.243241                    | 0.036255                              |
| 0.3                            | 1.260902                    | 0.053916                              |
| 0.4                            | 1.278002                    | 0.071016                              |
| 0.5                            | 1.296327                    | 0.089341                              |
| 0.6                            | 1.316967                    | 0.109981                              |
| 0.7                            | 1.334042                    | 0.127056                              |
| 0.8                            | 1.352339                    | 0.145353                              |
| 0.9                            | 1.369713                    | 0.162727                              |
| 1.0                            | 1.390157                    | 0.181371                              |
| 1.1                            | 1.408126                    | 0.201140                              |
| 1.2                            | 1.427023                    | 0.220037                              |
| 1.3                            | 1.445189                    | 0.238203                              |
| 1.4                            | 1.463533                    | 0.256547                              |
| 1.5                            | 1.482243                    | 0.275257                              |
| 1.6                            | 1.500013                    | 0.293027                              |
| 1.7                            | 1.518875                    | 0.311889                              |
| 1.8                            | 1.538761                    | 0.331775                              |
| 1.9                            | 1.558836                    | 0.351850                              |
| 2.0                            | 1.576273                    | 0.369287                              |
| 2.1                            | 1.595126                    | 0.388140                              |
| 2.2                            | 1.612054                    | 0.405068                              |
| 2.3                            | 1.627022                    | 0.420036                              |
| 2.4                            | 1.643344                    | 0.436358                              |
| 2.5                            | 1.657227                    | 0.450241                              |
| 2.6                            | 1.675491                    | 0.468505                              |
| 2.7                            | 1.691859                    | 0.484873                              |
| 2.8                            | 1.704533                    | 0.497547                              |
| 2.9                            | 1.720810                    | 0.513824                              |
| 3.0                            | 1.733936                    | 0.526950                              |
| 3.1                            | 1.748181                    | 0.541195                              |
| 3.2                            | 1.760685                    | 0.553699                              |
| 3.3                            | 1.770773                    | 0.563787                              |
| 3.4                            | 1.781470                    | 0.574484                              |
| 3.5                            | 1.796592                    | 0.589666                              |
| 3.6                            | 1.801024                    | 0.594038                              |
| 3.7                            | 1.805523                    | 0.598537                              |
| 3.8                            | 1.817925                    | 0.610939                              |
| 3.9                            | 1.823778                    | 0.616792                              |
| 4.0                            | 1.831941                    | 0.624955                              |
The least squares linear fitting is carried out on the data in Table 1, the Figure 4 is obtained. It can be seen from Figure 4 that the inductance value change of the inductance coil is approximately linear with the displacement of the magnetic core, but as the displacement of the magnetic core increases, the inductance value of the inductance coil gradually increases. However, when the magnetic core moves the same distance (for example, 0.1mm), the variation of inductance value first increases and then gradually decreases, for example, when the magnetic core moves from 0 to 0.1mm, the inductance value of the coil increases by 0.017398mH, when the magnetic core is moved from 3.9mm to 4.0mm, the coil inductance value is only increased by 0.008162mH. The reason for this situation is because the non-uniformity of the magnetic field of the inductance coil causes the input quantity (magnetic core displacement) and the output (coil inductance value) of the inductance coil presents a nonlinear relationship, and then affects the measurement accuracy of the inductance sensor.

![Figure 4. Fitting line of magnetic core displacement and coil inductance variation (simulation data)](image)

Linearity is an important index for evaluating performance of sensor, in order to get the output characteristics of inductance sensor; linearity is used to evaluate sensor performance [6]. The 0.5mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm, 3.0mm, 3.5mm, 4.0mm are selected as the sensor working range, and find the linearity of the sensor in the corresponding working range. The results are shown in Table 2.

| Working range | 0.5mm | 1.0mm | 1.5mm | 2.0mm | 2.5mm | 3.0mm | 3.5mm | 4.0mm |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Linearity     | 0.6%  | 0.7%  | 0.58% | 0.62% | 1.72% | 2.73% | 4.45% | 8.25% |

It is known from Table 2 that this inductance sensor can obtain better linear output characteristics within 2.0mm measurement range, and the linearity is less than 0.7%. After the sensor's measurement range exceeds 2.0mm, the linearity of the sensor becomes worse, and the larger the measurement range, the greater the linearity of the sensor, when the measurement range of the sensor reaches 4mm, the output linearity is 8.25%, which seriously affects the measurement accuracy.
4. Experiment
The relevant experimental platform is built to verify the analysis results. Figure 5 is the inductance sensor performance test bench which is composed of inductance sensor, precision linear guide, slider, laser interferometer, and an impedance analyzer. The slider is installed on the precision linear guide, the control slider moves linearly on the guide rail, the laser interferometer detects the displacement of the slider, the inductance sensor perceives the movement of the slider, and the inductance value change of the inductance coil of the inductance sensor is measured by the impedance analyzer.

Due to the internal structure limitation of the inductance sensor, the maximum movement range of the magnetic core is 3mm, and the control slider moves linearly in 0.1mm steps, due to the position error of the slider, the laser interferometer is required to calibrate the position of the slider, and the impedance analyzer is used to measure the inductance value of the inductance coil under the condition that the magnetic core in each position, as shown in Table.3.
Table 3 Wire inductance values at different positions of the slider

| Slide position (um) | Coil inductance L (mH) | Coil inductance variation ∆L (mH) |
|--------------------|-------------------------|---------------------------------|
| -0.1               | 2.86169                 | 0                               |
| 99.86              | 2.92860                 | 0.06691                         |
| 199.85             | 3.00171                 | 0.14002                         |
| 299.70             | 3.07169                 | 0.21000                         |
| 399.72             | 3.13803                 | 0.27634                         |
| 499.61             | 3.20988                 | 0.34819                         |
| 599.71             | 3.29015                 | 0.42846                         |
| 699.62             | 3.36078                 | 0.49909                         |
| 799.41             | 3.43023                 | 0.56854                         |
| 899.52             | 3.49911                 | 0.63742                         |
| 999.49             | 3.57383                 | 0.71214                         |
| 1099.35            | 3.64096                 | 0.77927                         |
| 1199.31            | 3.71276                 | 0.85107                         |
| 1299.28            | 3.78091                 | 0.91922                         |
| 1399.11            | 3.85105                 | 0.98936                         |
| 1499.08            | 3.92260                 | 1.06091                         |
| 1599.03            | 3.98184                 | 1.12015                         |
| 1698.98            | 4.05303                 | 1.19134                         |
| 1798.86            | 4.11896                 | 1.25727                         |
| 1898.90            | 4.19394                 | 1.33225                         |
| 1998.80            | 4.26002                 | 1.39833                         |
| 2098.68            | 4.32606                 | 1.46437                         |
| 2198.60            | 4.39117                 | 1.52948                         |
| 2298.58            | 4.44882                 | 1.58713                         |
| 2398.51            | 4.51168                 | 1.64999                         |
| 2498.48            | 4.56501                 | 1.70332                         |
| 2598.46            | 4.63537                 | 1.77368                         |
| 2698.40            | 4.69840                 | 1.83671                         |
| 2798.32            | 4.74721                 | 1.88552                         |
| 2898.27            | 4.80985                 | 1.94816                         |
| 2998.28            | 4.86043                 | 1.99874                         |

The data in Table 3 is used to draw the relation curve between the displacement of the magnetic core and the variation of inductance value of inductance coil, as shown in Figure 6. It can be seen from Figure 6 that in the actual working process, as the movement distance of the magnetic core increases, when the magnetic core move same displacement (for example, 0.1mm), the amount of increase of the inductance coil decreases. There is a nonlinear characteristic between the magnetic core displacement and the inductance coil variation, which is consistent with the conclusions of the previous analysis.
The output characteristics of the inductance sensor are calculated accordingly in 0.5mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm, and 3.0mm working range, the results are shown in Table 4. It can be seen from Table 4 that the linearity of this inductance sensor is less than 0.8% in the 2mm working range, when the working range exceeds 2mm, the output linearity of sensor increases significantly, reaches 1.93% in the 2.5mm working range, and reaches 2.53% in the 3mm working range.

| working range | 0.5mm | 1.0mm | 1.5mm | 2.0mm | 2.5mm | 3 mm |
|---------------|-------|-------|-------|-------|-------|------|
| linearity     | 0.61% | 0.79% | 0.53% | 0.57% | 1.93% | 2.53% |

It can be seen from Table 2 and Table 4 that there is an optimal working range for the output characteristics of the sensor, the output linearity of the sensor is smaller in this range. When this optimal linear working range is exceeded, the linearity of the sensor will become bad, and then affects the measurement accuracy of the sensor. This research provides a reference for the selection of measurement ranges in the using process of sensor. In the field of high-precision measurement, the measurement range should not exceed its optimal linear range (2.0mm), and the measurement range can be appropriately relaxed in occasion with low measurement accuracy.

5. Conclusion
The output characteristic function between the magnetic core displacement of the inductance sensor and the inductance variation of the coil is obtained through modeling and analysis of the inductance sensor. Correlation factors which affects the linear output characteristics of inductance sensors is obtained by function analysis of output characteristics of inductance sensor. Then simulation analysis of the inductance sensor is carried out and verified by experiments, it is proved that the magnetic core displacement of the inductance sensor has a nonlinear relationship with the variation of the coil inductance, the output linearity of the inductance sensor is better in a certain measurement range (less
than 2mm), and it is less than 0.8%. As the measurement range increases, the linearity of the inductance sensor becomes bad, and then seriously affects the measurement accuracy.

Through analysis of the output characteristics of the inductance sensor, provide a basis for the selection of the sensor's measurement range in engineering applications, the measurement range should not exceed its optimal working range in the field of high measurement accuracy (the linearity of this range is small), and the measurement range can be appropriately relaxed in occasion with low measurement accuracy.

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