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Research on direct digital process of inductance sensor

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Abstract The equivalent circuit of inductance sensor is analyzed. Amplitude-displacement and phase-displacement equations are deduced for non-ideal carrier wave and inductance parameters. Simulation computation shows the corresponding digital curves. Considering that the traditional process method is an approximate one, a new method is presented to simultaneously obtain the amplitude and phase of output signal of sensor by simultaneity A/D and ellipse fit arithmetic. According to the characteristic of the amplitude-displacement and phase-displacement curves, we obtain displacement by phase and amplitude respectively when the sensor is close to the zero point position and away from other positions on the basis of the experiment. The experiment showed that this method can improve precision of measurement, and it can also work for the whole linear range of sensors even if the magnification is very high.

Keywords inductance sensor, phase-displacement curve, ellipse fit, simultaneity A/D

1 Introduction

The theory of traditional signal process method is that the output signal is in-phase or anti-phase to the carrier excitation signal, such as the diode demodulation method, the analog switching demodulation method [1], and the digital phase sensitivity demodulation method [2] and so on. These methods rest on the one assumption that the inductance and the carrier wave are ideal [3]. But it is difficult to carry out. The continuity of the output signal phase’s variety and the existence of zero point remainder error of amplitude cause theoretical error. Along the path of the diode demodulation and the analog switching demodulation, the carrier wave signal will be influenced by the power frequency and the unstable circuit parameters. After filtering, the DC amplification signal will contain major power frequency AC signal [4, 5]. Considering that the frequency is low, the response speed of inductance will also slow down while filtering the power frequency signal in the high accuracy measurement. The nonlinearity error would occur for digital phase sensitivity demodulation, due to ignorance about the influence of the phase. Thus, the ellipse fit arithmetic and the separate identification of phase-displacement and amplitude-displacement were introduced in this paper, on the basis of strictly deducing the inductance sensor theory. It will improve precision, range and the speed of response.

2 The equivalent circuit of inductance sensor and theoretical output signal

The equivalent circuit of inductance sensor is shown in Fig. 1[3]. $U_b$, $U_c$ are carrier excitation signal; $r_1$ and $r_2$ are the internal resistance of inductance; $L_1$, $L_2$ are inductance quantity, $A$ is signal magnification. The two poles of inductance sensor load a uniform-amplitude, anti-phase AC excitation signal in theory. In fact, it is hard to meet the need. Applying the complex exponential form, assume $U_b$, $U_c$ are equal to the formula as follows:

$$\begin{align*}
U_b &= A_1 \exp(j\omega t) \\
U_c &= A_2 \exp[j(\omega t + \pi + \alpha)]
\end{align*}$$

(1)

Then if $r = r_1+r_2$, $L=L_1+L_2$, the output voltage will be written as Eq.(2)

$${U_O} = \frac{r}{J} \left[ {A_1 \exp(j\omega t) - A_2 \exp[j(\omega t + \pi + \alpha)]} \right]$$

(2)
\[ U_O = A \left[ \frac{U_B(joL + \gamma_1) + U_C(joL + \gamma_1)}{joL + r} \right] \]
\[ = \left[ A_2 \exp(joL + \gamma_2) + A_2 \exp \left[ j(\omega t + \alpha + \gamma) \right] (j(oL + \gamma_1)) \right] \]
\[ = \left[ A_2 \exp(joL + \gamma_2) + A_2 \exp \left[ j(\omega t + \alpha + \gamma) \right] (j(oL + \gamma_1)) \right] \]

\[ \frac{U_O}{U_B} = A - AK_p \left[ \cos \beta + K_A \cos(\alpha + \beta) \right] + jAK_p \left[ \sin \beta + K_A \sin(\alpha + \beta) \right] \]

If \( K_p = 1/2 \), \( K_A = 1 \), \( \alpha = 0 \), \( \beta = 0 \), then \( U_O = 0 \), that is, the output signal is zero when the excitation signal is ideal, \( \gamma_1 = \gamma_2 = 0 \) and the magnetic core is in the middle position of inductance. Suppose that \( s \) is inductance’s displacement, \( a \) is proportion coefficient of inductance and displacement. \( L_1, L_2 \) are the linear function of displacement as follows:

\[ L_1(s) = \frac{L}{2} + as \]
\[ L_2(s) = \frac{L}{2} - as \]

According to the definition of amplitude-frequency and phase-frequency, the correlation between the phase and displacement is shown by the Eq. (5), along with the amplitude and displacement, and the equation takes into account the change in range of phase from 0 to \( \pi \).

3 Digital curves and analysis of phase-displacement and amplitude-displacement

3.1 Digital Simulation of phase parameter \( \beta \) and proportion parameter \( K_p \)

Assuming that \( K_A = 1 \), \( \alpha = 0 \), \( \gamma_1 = \gamma_2 = 47 \Omega \), and designs parameters \( a = 0.004 \, \text{mH/\mu m}, \, L = 27 \, \text{mH}, \, \omega = 8\pi \times 10^5 \, \text{rad/s} \), \( A = 1 \, \text{000} \), calculate the relation curves of \( \beta \) to displacement and \( K_p \) to displacement when displacement changes from \( -30 \, \mu \text{m} \) to \( 30 \, \mu \text{m} \). Figures 2 and 3 show them respectively. We can see from these figures that \( \beta \) changes slowly, and \( K_p \) values changes linearly around 0.5. The traditional phase sensitivity demodulation methods are based on the state of the ideal inductance \( (\gamma_1 = \gamma_2 = 0) \) and the ideal carrier excitation. We can find that there are only 2 states for \( \phi(s) \) through calculation of Eq. (6), one is that \( \phi(s) = 0 \) when \( s \leq 0 \); another is that \( \phi(s) = \pi \) when \( s > 0 \). Through theoretical analysis, we find out that the approximate method causes measurement error and loses the accuracy of inductance in between times. In order to improve precision, the traditional demodulation methods must enhance extremely the magnification of the output signal, and it will lead to the magnification of noise. Hence traditional measurement methods are incapable of obtaining high