Nanometer Accuracy Amplitude Modulation Sensor Technique Used For Roundness Measurement

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Abstract. This paper introduces the advantage of digital phase sensitivity demodulation technique based on analyzing the errors of the analog phase sensitivity demodulation technique. And the digital phase sensitivity demodulation technique is used in the amplitude modulation sensor circuit for roundness measurement. The digital phase sensitivity demodulation technique can simplify the circuit design and improve the reliability. The experiment shows the amplitude modulation sensor circuit using the digital phase sensitivity demodulation technique can reach nanometer precision, so it can be used to accomplish the high precision roundness measurement.

1. Introduction
Phase sensitivity demodulation as an important means determines the ability for demodulating the low frequency and weak signals in the noise conditions. The conventional analog phase sensitivity demodulation circuit limits the precision improvement of the phase sensitivity demodulation because of the ripple influences[1-4]. The digital phase sensitivity demodulation technique that can be used to improve the demodulation precision is provided in this paper based on analyzing the errors of the analog phase sensitivity demodulation technique, and the amplitude modulation sensor circuit using the technique can reach nanometer accuracy and can be used for roundness measurement[5-7].

2. Principle of phase sensitivity demodulation
The principle diagram of the phase sensitivity demodulation that demodulates original signals \( g(t) \) from signals \( f(t) = g(t) \cdot \sin(2\pi ft) \) is shown in Figure 1.

\[ f(t) \rightarrow \text{PSD} \rightarrow U(t) \rightarrow \text{LPF} \rightarrow g(t) \]

**Figure 1.** Principle of phase sensitivity demodulation

\[ f(t) \rightarrow \text{Sample} \rightarrow \text{Quantization encoder} \rightarrow \text{Digital filter} \rightarrow g(n) \]

**Figure 2.** Principle of digital phase sensitivity demodulation
The frequency and phase of switch signal $V_R(t)=E_R\sin\omega t$ is same as the carrier wave signal. In order to improve the linearity the detection signal, the square wave signal $V_R(t)$ with the duty ratio 1:1 as same as the frequency of the carrier wave signal is often used:

$$V_R(t) = \begin{cases} 1 & nT \leq t \leq nT + \frac{T}{2}, \quad T = \frac{1}{f_0} \\ -1 & \text{else time} \end{cases}$$  \hspace{1cm} (1)

$V_R(t)$ is expanded as Fourier series:

$$V_R(t) = \frac{4}{\pi} \left[ \sin \omega t + \frac{1}{3} \sin 3\omega t + \cdots + \frac{1}{2K-1} \sin(2K-1)\omega t + \cdots \right] \quad (0 \leq x < \infty) \hspace{1cm} (2)$$

$$U(t) = f(t) \cdot V_R(t) = \frac{4}{\pi} g(t) \left[ \frac{1}{2} - \frac{1}{3} \cos 2\omega t - \frac{1}{15} \cos 4\omega t - \frac{1}{35} \cos 6\omega t - \frac{1}{(2K)^2 - 1} \cos 2K\omega t - \cdots \right] \quad (0 < t < +\infty) \hspace{1cm} (3)$$

It is known from equation (3), there are the other even harmonic signals with the base frequency $\omega$ besides the DC of measured signals $g(t)$ in the demodulation signals. In application, the low-pass filter is often used to eliminate the AC so as to obtain DC item $\frac{2}{\pi} g(t)$ of the original signal. But there are the following problems owing to the limitation of the filter:

1. It is difficult to eliminate totally AC component. The remained ruffle coefficient will effect the measurement precision, especially for high precision measurement;
2. DC component $\frac{2}{\pi} g(t)$ through demodulation can perform A/D conversion after DC amplification.

But DC signal is easily effected by low frequency noise, temperature drift, offset voltage and offset current when passing through DC amplification. It will reduce the amplification precision of the original signal;

3. The carrier wave signal and the reference signal will produce the phase drift each other. The phase difference $\varphi$ between the two signals will reduce demodulation sensitivity $\cos \varphi$ times;
4. The duty ratio of the reference square wave signal is difficult to guarantee 1:1. The asymmetry will bring the harmonic component to reduce the demodulation precision.

Because the above mentioned will restrict the improvement of the phase sensitivity demodulation precision, the digital phase sensitivity demodulation technique is introduced.

3. Digital phase sensitivity demodulation technique

3.1. Principle

The principle of digital phase sensitivity demodulation is shown in figure 3. Making use of the trait that the modulated signal $f(t)=g(t)\sin(2\pi ft)$ fluctuates smoothly at the wave crest and trough (the variation of $\frac{d}{dt} \sin \omega t = \omega \cdot \cos \omega t$ is zero at the wave crest and trough), the peak value which is proportional to the amplitude of original signal $g(t)$ can be obtained using the digital phase sensitivity demodulation principle.

Impulse sequence $P(t)$ with 2 times frequency of the carrier wave signal is used as the sampling impulse

$$P(t) = \delta(t) = \sum_{n=0}^{\infty} \delta[t-(nT+\frac{T}{4})]-\sum_{n=0}^{\infty} \delta[t-(nT+\frac{3}{4}T)] \quad (T = \frac{1}{f_0})$$ \hspace{1cm} (4)

Thus

$$U(n) = \sum_{n=0}^{\infty} f(t) \cdot \delta(t) = \sum_{n=0}^{\infty} f(t) \cdot \delta[t-(nT+\frac{T}{4})]-\sum_{n=0}^{\infty} f(t) \cdot \delta[t-(nT+\frac{3}{4}T)]$$ \hspace{1cm} (5)

g$n$ can be obtained by quantizing $U(n)$, digital treatment and smooth filtering, it is described as follows:
3.2. Process of digital phase sensitivity demodulation

The process of the digital phase sensitivity demodulation is shown in figure 4.

Signal $e(t)$ is the sampling initiate signal for the A/D conversion which is ascend edge triggering; $h(t)$ is the judgment signal of negative sign of the wave. The digital phase sensitivity demodulation is shown in the imaginary line frame in figure 4, the modulated signal passes through the band-pass amplification (its center frequency is $f_0=10$KHz), then processes A/D conversion directly. The frequency of the sampling start-up signal $e(t)$ is $2f_0$, the original phase angle difference between the original signal and the carrier signal is $\pi/2$. Having the ascend edge of $e(t)$ correspond to wave crest and trough of $f(t)$ ensures that the A/D converter can pick the wave crest and trough value. Then the computer can accomplish the digital phase sensitivity demodulation based on the detected ascend edge of $e(t)$, crest and trough value of $f(t)$, high and low electrical level of $h(t)$.

In order to improve the measurement precision, a high speed A/D converter is used to sample with high speed and average for many sampling data ($N \approx 100$):

$$g(n) = \frac{1}{N} \sum_{n=1}^{N} \left[ S_{(n+1/4)T} - S_{(n+3/4)T} \right]$$

(6)

From the working process of the digital phase sensitivity demodulation, it is known that the carrier wave signal with AC amplification and conversion in the whole signal channel can avoid the DC
amplification and consequently eliminate the effects caused by the asymmetry of reference square signal and the remained ripple coefficient.

4. Application and experiment

4.1. Application example
A conversion circuit of amplitude modulation inductive sensor is developed by using the digital phase sensitivity demodulation technique.

![Figure 5](image)

**Figure 5.** Principle diagram of amplitude modulation conversion circuit of inductance sensor.

4.2. Experiment verification
The micro-measurement sensor system was used in the roundness measuring instrument. To examine the stability of the micro-measurement sensor system, the sensor system measures a fixed artifact 1024 data in 15 seconds (roundness measurement takes about 15 seconds to measure a circle), and 1024 data are filtered using 1-15upr and performed error assessment using least square circle method. Then the stability error of the indicating value of the sensor system is obtained and be 2nm, The data are shown table 1, and the circle curve is shown in Figure 6.

![Figure 6](image)

**Figure 6.** Stability test of the sensor system used in the roundness instrument
| Table 1. Stability data after filtering |
|--------------------------------------|
| Testing times | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
| Stability error (nm) | 2.0 | 1.8 | 1.4 | 2.0 | 1.2 | 1.6 | 1.6 | 1.4 | 1.6 | 1.8 |

5. Conclusion
The digital phase sensitivity demodulation technique can avoid the DC signals amplification and eliminate the influence caused by the ripple existed in analog phase sensitivity demodulation circuit. It can improve the detection sensitivity and reliability, and simplify the circuit.

References
[1] Bayard J 1998 An improved method of generating analog waveforms from digital data Rev. Sci. Instrum 69 2569-71
[2] Marioli D, Sardini E and Taroni A 1998 High accuracy measurement techniques for Capacitance Transducers Meas. Sci. Technol. 9 510-517
[3] Zhou S M 1995 Error analysis of sinusoidal wave generated by digital synthesis technique Journal of Instrument Technique 4 18-20
[4] Chen J G 1980 Phase sensitivity demodulator Journal of Instrument and Apparatus 1 108-115
[5] Wang J and Lu G 1998 Review of minimum detection signal of the nanometer displacement sensor Journal of Transducer Technology 17 1-5
[6] Zhang S Y, Yu P and Zhu P X 1998 The research to reducing the noise of the sensor demodulation circuit Journal of Instrument and Apparatus 19 158-162
[7] Tan J B, Zhao W Q and Yang W G 2000 Development of Research on Super-precision Measurement Technique for circle and cylindrical contour (Invited Paper) Proceeding of SPIE 4222 0277-786X/00