Research on Sensor Differential Measurement with Transmission Line Vibration Detection System

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Abstract. In this paper, the transmission line system is used as a model to detect the vibration of the transmission line ground wire. The circuit and transmission characteristics of sensor differential method are discussed in detail. The application of sensor differential method in transmission line vibration detection system is analyzed in time and frequency domain. The experimental results show that sensor differential mode is greatly improved than single sensor on sensitivity, linearity and frequency characteristics in vibration measurement of transmission line.

1. Introduction
Transmission line is an important part of power system, which is responsible for the transmission and distribution of electric energy. In the operation of transmission line, the aeolian vibration of conductor and ground wire occurs frequently, which often leads to the conductor and ground wire fatigue breaking. The characteristics of aeolian vibration are small amplitude, high frequency and long duration. The amplitude is generally smaller than the diameter of the conductor, and the maximum can reach 2-3 times of the diameter of the conductor. Generally, the vibration frequency is 10~50Hz, and the maximum frequency is about 100Hz. The vibration time can last for several hours.[1,2]

According to the above characteristics of transmission line aeolian vibration, this paper uses inductive proximity sensor to detect the transmission line vibration. The output voltage of the sensor changes with the vibration of the transmission line. The transmission characteristic curves of sensor difference method and single sensor method are measured by experiments. The advantages of the sensor differential method are analyzed and discussed.

2. System composition design
The flow chart of transmission line vibration detection system designed in this paper is shown in Figure 1

![Flow chart of transmission line vibration detection system](image)

The output signal of the sensor is output through the voltage bias circuit, filter circuit and amplification circuit. The data is collected by the single-chip microcomputer system and sent to the computer. The data is analyzed by software and the vibration characteristic curve of the transmission line is obtained by curve fitting. The parts in Figure 1 are introduced as follows:

2.1. Sensor introduction
The sensor adopts inductive proximity sensor, which belongs to non-contact measurement. It is widely
used in the precise measurement of displacement, vibration, angle, acceleration and other mechanical quantities. It has a place in many sensors because of its small power, high impedance, small electrostatic attraction and small thermal effect.

The sensor consists of three parts: oscillator, switch circuit and amplifier output circuit. The oscillator generates an alternating magnetic field. Through the sensing surface of the sensor, the oscillator generates a high-frequency alternating electromagnetic field in front of it. When the metal target approaches the magnetic field and reaches the sensing distance, eddy current will be generated in the metal target. The eddy current will react on the proximity sensor, resulting in vibration attenuation and even vibration stop. The change of oscillator oscillation and stop vibration is processed by the post amplifier circuit and converted into switch signal, which triggers the driving control device, so as to achieve the purpose of non-contact detection.

2.2. Voltage bias circuit

The output voltage of the sensor passes through a bias circuit composed of a precise reference source to ensure that the output signal is in the linear range of the amplifier. Adjust the adjustable resistance to make the output voltage of the transmission line in the stable state and the high-precision, low-temperature drift OP-07 is used in the amplification circuit.

The output voltage is as follows:

\[ U_o = R_{14} \left( \frac{U_{i1}}{R_{12}} - \frac{V_{ce}}{R_{11} + R_1} \right) \]  

(1)

2.3. Low pass filter circuit

The output voltage of the former stage bias circuit passes through the second stage active low-pass filter circuit. The circuit shown is a voltage controlled voltage source circuit, in which the op amp is in-phase input, the input impedance is very high, the output impedance is very low, and the filter is equivalent to a voltage source. The circuit performance is stable and the gain is easy to adjust.

The voltage gain of the second-order low-pass filter is as follows:

\[ A_v = 1 + R_{16} \]  

(2)

The cut-off frequency of the low-pass filter is as follows:

\[ \omega_c = \frac{1}{\sqrt{R_{15}R_{16}C_{11}C_{12}}} \]  

(3)

Take the filter quality factor \( Q = 0.0707 \), and the voltage gain \( A_v \) and cut-off angle frequency \( \omega_c \) meet the following relationship:

\[ \frac{\omega_c}{Q} = \frac{1}{R_{15}C_{12}} + \frac{1}{R_{16}C_{12}} + (1 - A_v) \frac{1}{R_{16}C_{11}} \]  

(4)

The transfer function of the display filter circuit is

\[ A(s) = \frac{A_v \omega_c^2}{s^2 + \frac{\omega_c}{Q} + \omega_c^2} \]  

(5)

2.4. Amplification circuit

The amplification circuit adopts integrated differential amplification circuit, which has a good amplification effect on differential mode signal, can effectively suppress common mode signals such as temperature drift, and improve the sensitivity of the vibration detection system. AD623 is an instrument amplifier based on the improved traditional three operation amplifier scheme, which can provide good linearity, temperature stability and reliability, and is widely used in low power consumption Medical instruments, sensor interface, differential amplification and low power data acquisition. The gain can be determined by formula \( G = 1 + 100 / R \), and the gain multiple can be set by
3. Research on sensor differential method

The sensor differential detection circuit\[7\] uses two identical sensors, one as a forward sensor and one as a reverse sensor. The two sensors are placed in the same environment. When the detected object offsets $\Delta x$ to the forward sensor and $-\Delta x$ to the reverse sensor, the output voltage of the forward sensor increases and the output voltage of the reverse sensor decreases, and the output voltage of the forward sensor $U_1$. And the reverse sensor output voltage $U_2$ as the output voltage.

The differential method is used to detect the vibration of transmission line. The two sensors are proximity sensors with the same structure. The output characteristic curve of each sensor is measured, and the two sensors with similar sensitivity are installed in pairs. The sensor is installed on both sides of the transmission line. Adjust the zero adjustment resistance so that the output is 0, which is the zero point of the output characteristic curve.

3.1. Strong anti-interference ability

The single sensor will bring errors to the measurement when it is interfered by the external environment and temperature changes. To reduce the influence of these interferences, measures should be taken in the measurement method and the measurement circuit, and the differential method should be used for this kind of interference. When the common mode interference acts, the output of the forward sensor and the reverse sensor increases by a number $K\Delta x$ at the same time, and the differential output voltage is as follows:

$$
\Delta U = U_1 - U_2 = (\Delta U_1 + K\Delta x) - (\Delta U_2 + K\Delta x) = \Delta U_1 - \Delta U_2
$$

From equation 6, it can be seen that the sensor differential method has a strong anti-interference ability, especially for the common mode interference which affects the two sensors at the same time, such as the change of environment temperature and electromagnetic interference.

3.2. High sensitivity

If the sensitivity of the two sensors is $K_1$ and $K_2$ respectively, the output voltages $\Delta U_1$ and $\Delta U_2$ of the two sensors meet the following requirements:

$$
\Delta U_1 = K_1 \Delta x \\
\Delta U_2 = -K_2 \Delta x
$$

Sensitivity

$$
K_s = \frac{\Delta U}{\Delta x} = \frac{\Delta U_1 - \Delta U_2}{\Delta x} = \frac{K_1 \Delta x - (-K_2 \Delta x)}{\Delta x} = K_1 + K_2
$$

It can be seen that the sensitivity of the sensor differential method is the sum of the sensitivity of the two sensors.

3.3. Improve nonlinearity

The static characteristic of the sensor is $U = e^{Kx} - 1$, which belongs to nonlinear characteristic. When $x = x_0$, output voltage $U = U_0$, when $x = x_0 + \Delta x$, output voltage $U = U_0 + \Delta U$, the voltage offset $\Delta U$ can be obtained as follows:

$$
\Delta U = U - U_0 = (U_0 + 1)(e^{\Delta x} - 1)
$$

When the differential method is used for measurement, the output characteristics of the two sensors are as follows:

$$
U_1 = e^{\Delta x} - 1 \\
U_2 = e^{-\Delta x} - 1
$$

The voltage offset of each sensor meets the following requirements:
The Taylor series expansion of voltage offset is as follows:
\[
\Delta U_1 = (U_o + 1)e^{e^x} - 1
\]
\[
\Delta U_2 = (U_o + 1)e^{-e^x} - 1
\]
(11)

The total output of the differential method is as follows:
\[
\Delta U = 2k\Delta x(U_o + 1)[1 + \frac{1}{2!}(k\Delta x)^2 + \cdots + \frac{1}{n!}(k\Delta x)^n + \cdots]
\]
(12)

The output sensitivity of differential method is as follows:
\[
K_{df} = \frac{\Delta U}{\Delta x} = 2k(U_o + 1)[1 + \frac{1}{3!}(k\Delta x)^2 + \frac{1}{5!}(k\Delta x)^4 + \cdots + \frac{1}{(2n-1)!}(k\Delta x)^{2n-2} + \cdots]
\]
(13)

The above part of the primary term of \( \Delta x \) reflects the severity of nonlinearity. It can be seen that the primary term (including all odd terms) reflecting the more serious nonlinearity does not exist, thus improving the nonlinearity of a single sensor.

3.4. Enhanced frequency characteristics
The sensor is equivalent to a simple circuit model (as shown in Figure 2 and figure 3). The sensor differential method can be understood as two input and one output equivalent circuits to calculate the frequency characteristics of the sensor.

For a single sensor:
\[
W(s) = \frac{U_o}{U_i} = \frac{R}{R_s + R_s + SL}
\]
(15)

For sensor differential method:
\[
W_{df}(s) = \frac{U_o}{U_i} = \frac{R_s + R_s + S(L_s + L_2)}{R_s + R_s + S(L_s + L_2)} \cdot \frac{(M_s + M_o)_s}{(T_s + 1)(T_s + 1)}
\]
(16)

It can be seen from the above formula that compared with a single sensor, the frequency response range is increased by adopting the differential method.

4. Analysis of experimental results
4.1. Static characteristic analysis of sensor
Change the distance between the transmission line and the sensor in Figure 4, and measure the voltage output characteristic curve of single sensor input and sensor differential input respectively.
It can be seen that in the case of single sensor input, when the transmission line is close to the sensor, the sensor detection is more sensitive and the linearity is better. When the transmission line is far away from the sensor from the balance point, the sensor output changes little. When the sensor differential method is used, the sensitivity is significantly higher than that of a single sensor, and the linear range is twice that of a single sensor.

4.2. Frequency range analysis

In the same way, a vibration source is added to the transmission line to measure the frequency characteristics of the transmission line when a single sensor input and differential input are used. The input signal $V_i$ with fixed amplitude and adjustable frequency is given by the signal generator, and the vibration source signal is given by the power amplifier to make the transmission line vibrate. The measured output voltage $V_o$ is based on the frequency change characteristic curve of $V_i$, as shown in Figure 5.

It can be seen from Figure 10 that the frequency range detected by a single sensor is between 10Hz and 90Hz, while the detectable frequency input by the sensor differential mode is between 5Hz and 130Hz, and the frequency response $V_o/V_i$ of the sensor differential method is also higher than that of the single sensor input.

Based on the above analysis data, the comparison table of the characteristics of sensor differential detection and single sensor detection is shown in Table 1 below:
Table 1 Comparison of sensor differential detection

| Detection method        | Common mode rejection | Sensitivity (V/mm) | Linear range (mm) | Voltage gain | Frequency range (Hz) |
|------------------------|-----------------------|-------------------|-------------------|--------------|----------------------|
| Individual sensor      | no                    | 0.8               | 4                 | 12           | 100                  |
| Sensor difference      | yes                   | 1                 | 8                 | 23           | 130                  |

5. Conclusion
The conclusion can be drawn from the experimental measurement data obtained from the experimental simulation of transmission line vibration system: in the vibration detection system, compared with the input mode of single sensor, when the inductive proximity sensor adopts differential detection mode, it increases the anti-interference ability, improves the suppression ability of temperature, electromagnetic interference and other external environmental influences, improves the sensitivity of the system, improves the nonlinearity of the system, and widens the frequency range.

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