Measurement circuit of solenoid inductance sensor

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Abstract

To achieve the accurate measurement of the hydraulic valve opening position, two different measurement circuits were designed respectively for two-coil and three-coil differential solenoid inductance displacement sensors. Compared the pros and cons of their static and dynamic performances. The peripheral measurement circuit based on the AD698 was improved, so as to enhance the sensitivity of displacement detection. The different sensor measurement circuits were tested to compare the static output characteristics of these two types of sensors. The experimental results show that AD698 sensor measurement circuit is featured with small nonlinear error, high repeatability, and low hysteresis error. Sensitivity varies with the range of the measurement. When the sensor measuring ranges of conditions are defined, it is appropriate to increase sensitivity. In Valvistor hydraulic cartridge valve system, AD698 measurement circuit would be used to test the real-time dynamic detection. When the system pressure is maintained constant, the valve opening size influences the response speed of the sensor measuring circuit. The greater the pressure valve, the faster the dynamic response of the valve. The relationship between main valve displacement and flow rate is also detected in these experiments.

Keywords: differential solenoid inductor sensor, detection circuit, AD698, sensitivity

1 Introduction

The static and dynamic performance of proportional directional valve control system are improved by employing real-time displacement feedback technology and potential displacement correction technology. High sensitivity, low nonlinearity error, good reliability and long service life make inductive displacement sensor widely used in harsh environments like in oil and in high temperature [1, 2]. In the displacement detection system, Alternating voltage signal is converted into a DC signal proportional to the displacement by processing the circuit. The displacement signals are then processed by DSP [3]. To improve the control performance of the system, requirement of the circuit design is that the real-time displacement measurement of the sensor must be precise.

The sensors use the differential structure to eliminate nonlinear error, zero error, and drift. When the sensor type is determined, the sensitivity and accuracy of the measurement will be known. To ensure the accuracy of the displacement measurement, the sensor signal processing circuit must have a high sensitivity and accuracy. The measurement circuit provides a stable excitation signal for driving the electromagnetic coil, carrier frequency is usually 10 times greater than or equal to the bandwidth of the sensor. Since the change of spool displacement causes the change of coil impedance variation, the voltage signal corresponding to the displacement will be obtained by the modulation and demodulation circuit. The common methods of displacement measurement sensor circuit are monolithic signal conditioning chip, the AD698, AD598, AD630, differential rectifier circuit and a detection circuit. A AD698 circuit was improved to measure the inductive displacement sensor [4]. The operational principle of circuits for voltage-switching phase sensitive detector were described [5]. Designed a high precision radiation-tolerant LVDT conditioning module, which can use AD698, AD598, SE5521 and SIA [6]. The design of the LVDT actuator uses AD598 chip to form a signal test circuit [7]. AD698 chip was used in a pneumatic micro actuator to test the movement of the cylinder of the actuator [8, 9]. In addition some circuits was also designed and compared for inductive sensors [10].

2 The characteristics of differential solenoid inductor sensor

The Differential solenoid inductive displacement sensor in the proportional valve measurement can transform the linear displacement into the Coil inductance. It is composed of the solenoid coil with average radius-r, the armature and the magnetic sleeve. The coil inductance will be changed with different depths of armature insertion, which will cause changes in coil leakage path reluctance. When the turns and materials permeability inductive sensor is determined, the inductance changes are caused by the geometry change of the coil magnetic circuit led by the displacement change of the armature. When sinusoidal excitation is applied, the DC voltage proportional to the displacement will be obtained.

As shown in Figure 1a, the differential solenoid self-inductance sensor is commonly two coils. Its circuit principle is shown in Figure 2a. The two coil resistances are Z_1 and Z_2.

$$\begin{gathered} Z_1 = Z_2 = Z, \quad L_1 = L_2 = L_0, \quad r_1 = r_2 = r_0, \\ Z_1 = r_1 + j\omega L_1, \quad Z_2 = r_2 + j\omega L_2 \end{gathered} \tag{1}$$

where r_1 and r_2 are the internal resistance of the two coils, L_1 and L_2 are the inductance of the two coils and L_0 and r_0 are the initial inductance and internal resistance.

During the operation, by providing incentive power supply E to the sensor, then the output voltage U_0 is:

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$$\dot{U}_0 = \frac{\dot{E}}{2}\cdot\frac{\Delta Z}{Z} = \frac{\dot{E}}{2}\cdot\frac{\Delta r + j\omega\Delta L}{r_0 + j\omega L_0}, \quad (2)$$

where ΔL is the variable quantity of inductance, Δr is the variable quantity of internal resistance.

The structure of the three-coil differential solenoid inductance sensors is shown in Figure 1b, and its circuit schematic is in Figure 2b. If the structure of the sensor is ideally symmetrical, the self-induction and mutual-inductance is equal when the activity armature in the initial equilibrium position.

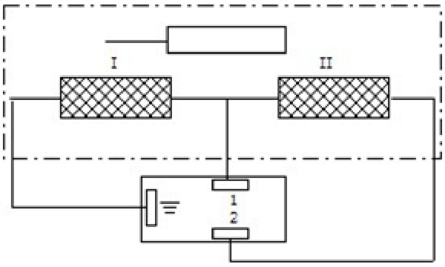


FIGURE 1a Structure of two-coil sensor

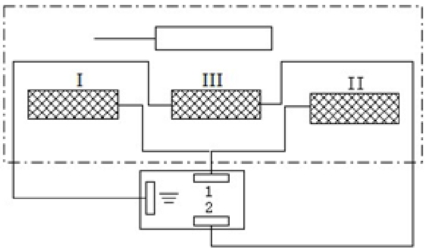


FIGURE 1b Structure of three-coil sensor

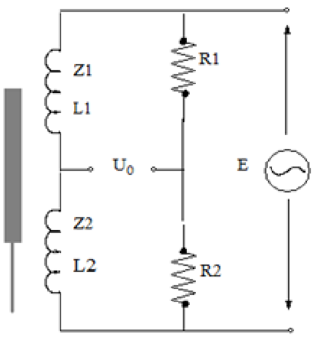


FIGURE 2a Equivalent circuit of two-coil sensor

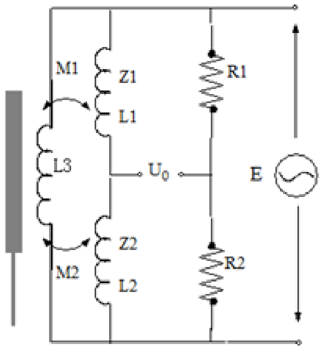


FIGURE 2b Equivalent circuit of three-coil sensor

According to electromagnetic induction principle, the electromotive force is $E_1=E_2$.When the armature has offset from the centre position, the output voltage U_0 is:

$$\begin{aligned}\dot{U}_0 &= j\omega\Delta M \dot{I}_1 + j\omega\Delta L \dot{I}_2 + \Delta r \dot{I}_2 \\ &= j\omega\Delta M\cdot\frac{\dot{E}}{r_3 + j\omega L_3} + j\omega\frac{\Delta L}{2}\frac{\dot{E}}{r_0 + j\omega L_0} + \frac{\Delta r}{2}\frac{\dot{E}}{r_0 + j\omega L_0}. \\ &\approx j\omega\Delta M\cdot\frac{\dot{E}}{r_3 + j\omega L_3} + j\omega\frac{\Delta L}{2}\frac{\dot{E}}{r_0 + j\omega L_0}\end{aligned} \quad (3)$$

3 Measurement amplifier circuit of inductive sensor

3.1 DETECTOR CIRCUIT

If measurement amplifier circuit of inductive sensor uses detector circuit, it can determine the armature movement direction, improve the output characteristics, and reduce the residual voltage at the zero position. The circuit generally consists of five parts, i.e. concussion, amplified, phase following, detection, and filtering. This circuit has features of low cost, simple structure, high frequency, convenient debugging, but also with low precision, which is a common drawback of the analogue circuits.

1) Sine wave generating circuit

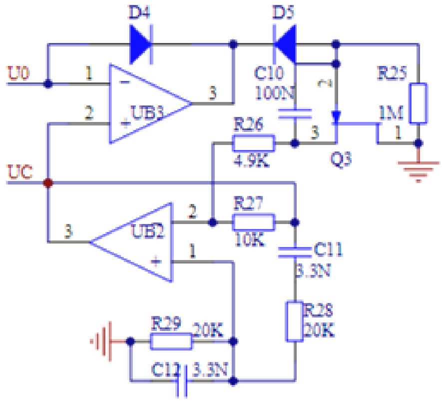


FIGURE 3 Wien bridge sine oscillator circuit

The circuit provides excitation signal for the coil, and the synchronization signal for detection circuit. Wien bridge sine oscillation circuit is used. As shown in Figure 3, frequency of the oscillation is 2.41 KHz. Integrated OA UB2 consists amplifier circuit, and the series- parallel frequency selective network includes R28, C11 and R29, C12. One output of network with positive phase of the input of the OA UB2 constitutes a positive feedback. Another output link with partial pressure circuit R26 and R27 connecting the reverse phase input, constitutes a negative feedback amplifier circuit. UB3, D4, D5 and Q3 constitute a steady vibration circuit. To generate self-excited oscillation in circuit, start-up condition is to gain AF>3, and Q3 is cut off. When the amplitude is stable, the gain AF is equal to 3, and Q3 is on. The feedback intensity of the amplifier automatically adjust can be used to achieve amplitude stability. When the amplitude increases, the negative feedback factor automatically increases. Enhanced negative feedback effect can inhibit the amplitude increases. Conversely, the negative feedback effect is weakened, and the amplitude decreases.

2) Square wave generating circuit

Sine wave through the C8, UB1 produces synchronization square wave signal with frequency of 2.41 KHz (Figure 4).

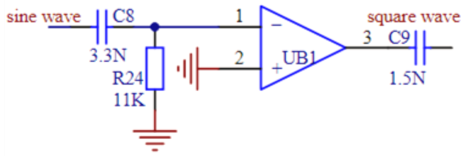


FIGURE 4 Square wave generating circuit

3) Dc measurement amplifier circuit output

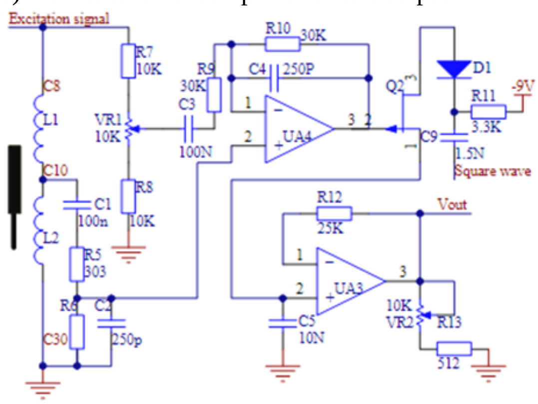


FIGURE 5 Dc output of measurement amplifier circuit

As shown in Figure 5, the circuit includes differencing, detection, amplifier and filtering. When the armature is in middle position, the potentiometer VR1 will balance the value of the bridge so that the zero residual voltage is eliminated and output voltage Vout is 0. When the armature moves upward, the impedance of the coil L_1 increases and the impedance of the coil L_2 decreases. Sine-wave voltage signal U_1 will be obtained by the phase-shift and differencing amplifier UB2 circuit. When the U_1 is negative, Q_2 is conductive. When the U_1 is positive, Q_2 is cut-off. Then stable positive voltage Vout corresponding to armature displacement can be obtained by half-wave detection. When the armature moves downward, the impedance L_1 decreases and the impedance L_2 increases. As the same, when Q_2 is on, the Vout is an output negative voltage corresponding to the displacement. Switching half-wave detector circuit achieves its purpose as desired by test of the actual measurement.

3.2 MEASUREMENT AMPLIFIER CIRCUIT OF THE SENSOR BASED ON AD698

The measurement circuit can also be achieved by using AD698. AD698 is a high precision modem chip, which integrates a perfect signal conditioning system of differential displacement sensor, with a wide range of applications including the modulation and demodulation, synchronous detection, phase detection. The chip of AD698 consists of a low distortion sine wave generator, a power amplifier, a proportional circuit, a filter circuit, two-channel synchronous demodulation passage A, B and an amplifier output circuit. AD698 has excellent performance, which can eliminate the unfavourable factors of the interface between the traditional signal conditioning circuit and the voltage differential displacement sensor without internal compensation circuit [11].

According to the manual of AD698 chip, the external circuit main components should be calculated and selected. The output of AD698 measuring circuit is:

$$V_{OUT} = \frac{V_A}{V_B} \times I_{REF} \times R_2 + V_{OS}, \quad I_{REF} = 500\mu A \tag{5}$$

where V_A and V_B are the input voltage of synchronous demodulation A and B channels, V_{OS} is the bias voltage.

$$V_{OS} = 1.2V \times R_2 \times \left(\frac{1}{R_3 + 2K\Omega} - \frac{1}{R_4 + 2K\Omega} \right). \tag{6}$$

The elevation of the sensitivity can effectively improve the measurement accuracy of the circuit. As seen from the Equation (5), there are three methods that can enhance the sensitivity of the measuring circuit (Figure 6).

1) Amplify the output signal of AD698 (V_{OUT}).

Enlarge the output VOUT which also amplifies the noise signal.

2) Amplify the input signal of channel A(VA).

The maximum amplitude of the input of channel A is 3.5V. The sensitivity cannot be effectively improved due to the amplification limit of the channel A input signal in the case of a large excitation voltage.

3) Minify the input signal of channel B(VB).

This is the best method that can effectively improve the sensitivity. In order to ensure that the AD698 input V_A/V_B falls in the range [-1 1]. Channel A must uses the bridge connection. When the armature is at the middle position, in order to make the input of the channel A zero, the R_7 is adjusted. So the AD698 input V_A/V_B is 0.

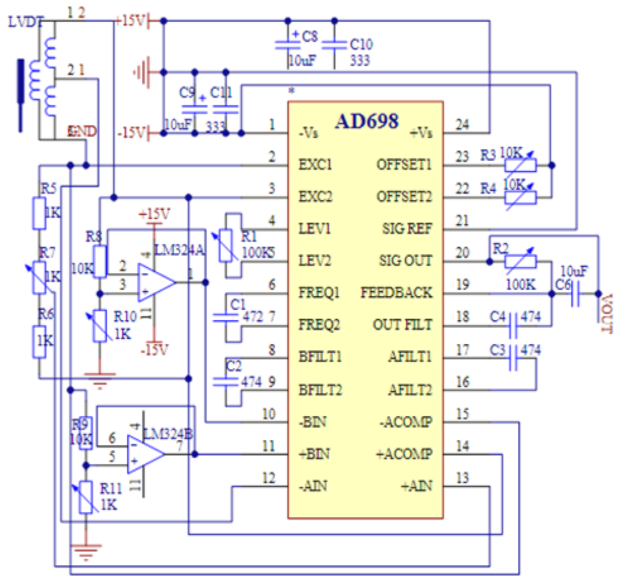


FIGURE 6 AD698 measurement circuit of displacement inductive sensor

4 Detection and analysis of the circuit static properties

Figure 7 and 8 show the structure of the measuring equipment for the displacement sensor circuit characteristics. This measuring equipment can be used to test dynamic characteristics of proportional control valve through tap water-experimental examination [12]. The three-coordinate measuring machine is utilized to accurately measure the tiny spool displacement.

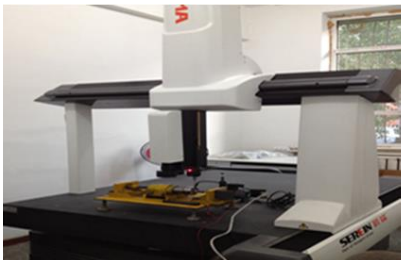


FIGURE 7 Experimental picture

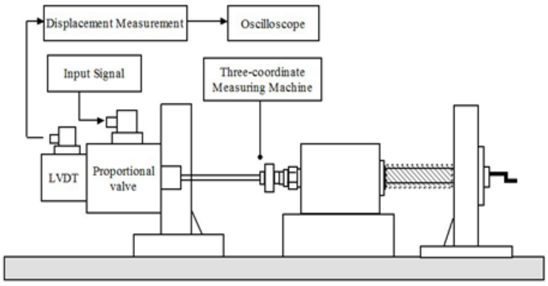


FIGURE 8 Structure of measuring equipment for displacement sensor circuit characteristics

4.1 STATIC OUTPUT CHARACTERISTIC OF TWO DIFFERENTIAL INDUCTIVE SENSOR

The three-coordinate measuring machine is used to measure the static displacement of two different sensors, the results of the measurement is shown in Figure 9. The static output characteristic of two differential inductive sensor uses AD698 measuring circuit. Figure 9a is the curve of three-coil differential inductive sensor. It shows that the range of the good linearity is from 0.67mm to 9.21mm. Therefore the effective travel X1 of the three coil differential inductive sensor is approximately 8.5mm and nonlinear error is 0.6%. Figure 9b is the curve of two-coil sensor. The range of the good linearity is from 5.44mm to 15.63mm. So the effective travel X2 of the two coil sensor approximately is 10mm. And nonlinear error is 3.3%.

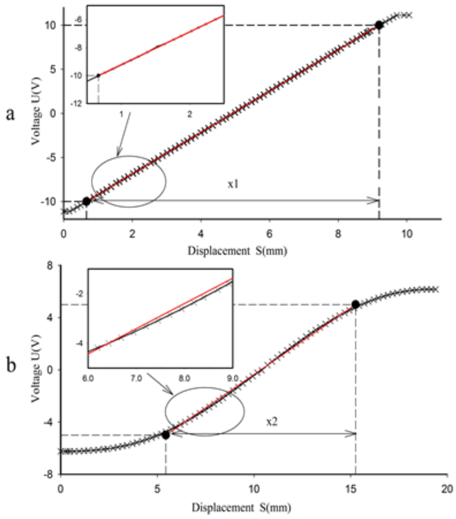


FIGURE 9 Static output characteristic of two differential inductive sensor

The results of the comparison of the two sensor are as follows. The travel of the two-coil sensor is longer than the three coils sensor, but the linearity is worse seen from the partial enlarged view curve. So the three-coil differential inductive sensor could be used well in accurate measurement of high linearity and small measure displacement.

4.2 IMPACTION OF THE SENSITIVITY TO THE STATIC CHARACTERISTIC OF THREE-COIL INDUCTANCE SENSOR TESTED BY AD698 CIRCUIT

The sensitivity of the sensor measuring circuit could be changed by adjusting potentiometer R_{10} and R_{11}. So changing the input of the channel *B*. When R_{10} and R_{11} are increased, V_B will be decreased, so V_{OUT} and sensitivity are improved. Conversely, R_{10} and R_{11} are reduced, the sensitivity will be decreased.

Figure 10 shows the static measurement characteristic when the sensitivity of the AD698 circuit is difference. The effective measurement range of the sensor is 8.5mm.Seen from the figure when the sensitivity becomes higher, the range becomes smaller. The right of the Figure 10 is the comparison chart that meets the different degree of measurement range. The maximum sensitivity is S4, but the linearity is less than the sensitivity S5 at both ends of the largest displacement measurement. When the sensitivity is 2.4V/mm, it meets the range, and has a good linearity. It not only improves the sensitivity, but also meets the requirements of the sensor range.

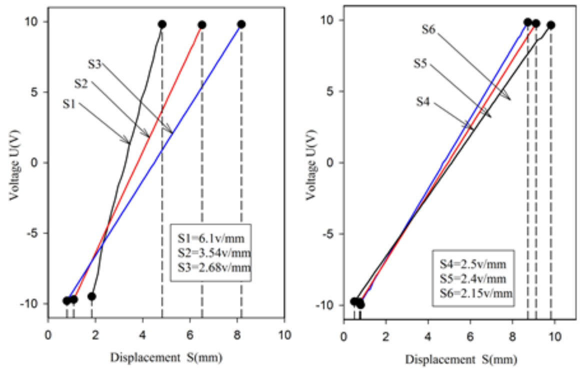


FIGURE 10 Different sensitivity of the AD698 circuit

4.3 DETECTION AND ANALYSIS OF THE STATIC PROPERTIES OF THE TWO MEASURING CIRCUITS

At the same calibration, multiple measurements of forward and reverse trip for will be done. It happens three times.

P represents the process, B represents the return-trip. Repeatedly measuring the linear range of voltage-displacement relationship, the range of the voltage measurement is -10V~ +10V. The repeated accuracy is 0.284%, and the maximum error of the hysteresis between the process and the backhaul is 0.29%. From the result of the measurement, the AD698 circuit is good at detecting the movement of the hydraulic spool, and has high repeated accuracy and hysteresis. But the result of the displacement measurement has a tiny temperature drift when the circuit boards had been used a long time. So it is applicable a small temperature changes.

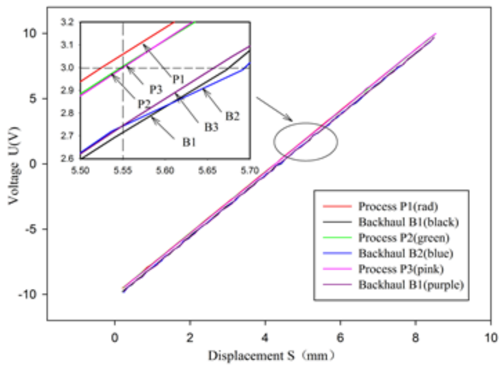


FIGURE 11 Static performance measurements tested by AD698 circuit

Figure 12 is the result of the static displacement measurement of the half-wave detection measurement circuit, the measurement range is -6V~ +6V. The accuracy of the repetition is 0.441%. The maximum error of the hysteresis between the process and the backhaul is 0.28%. Comparing the measurement results of two different circuits, the repeated accuracy of the AD698 measurement circuit is higher, and the non-linearity error is smaller. The half-wave detection circuit is more stable, so the temperature drift can be ignored.

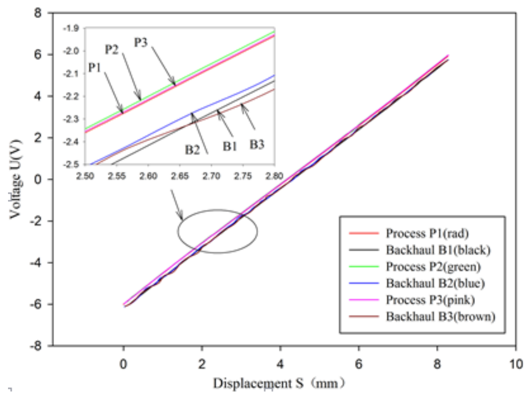


FIGURE 12 Static performance measurements tested by detection circuit

5 Detection and analysis of the circuit static properties

5.1 DYNAMIC TEST OF SPOOL DISPLACEMENT OF PROPORTIONAL VALVE WITHOUT HYDRAULIC SYSTEM

With different voltage being applied to the proportional valves, when the voltage is larger, the force that the armature of proportional valve suffers is greater, the faster the armature moves and the larger the slope ratio gets.

Figure 13 is the dynamic performance of proportional valve tested by half-wave detection circuit. When 15V is powered to the proportional valve, dynamic performance of proportional value reaches the range of linear measurement after 15ms delay. From the figure, when a different voltage is applied to the proportional valve, there exists a non-linear portion. The smaller the power voltage is, the more obvious the non-linear is. The slope of A-B section is larger in the figure, and the voltage changes greatly with time. The slope of B-C section is smaller, and the voltage changes smaller with time. The reasons for this result are as follow. Firstly, because of the unsuitable quiescent point for transistor and the bad linearity, the amplifier magnifies not only the input signal, but also the higher harmonics of the input signal. Secondly, there is a capacitor C6 of the amplifier circuit. Capacitor is charging when positive voltage is added on the both side of the capacitor, so the capacitor has residual voltage that causes the storage of charge on one side of the capacitor and the storage of electron on other side. When put reverse voltage on the capacitor, due to the presence of residual voltage, the electrons move fast, and the slope is larger.

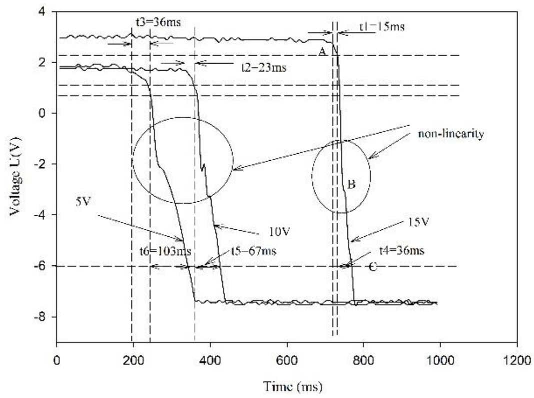


FIGURE 13 Dynamic measurements of the detector circuit for proportional valve

When the proportional valve is added different voltage, Figure 14 is the dynamic characteristics of the AD698 measurement circuit for the spool of the valve which moves transiently. The minimum delay is 10ms when the valve is energized to 15V. The measurement results reach linear range. The linearity is excellent under different voltage. The voltage corresponding to displacement signal can be measured timely and accurately.

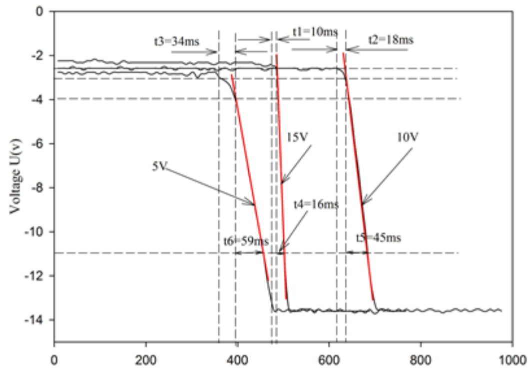
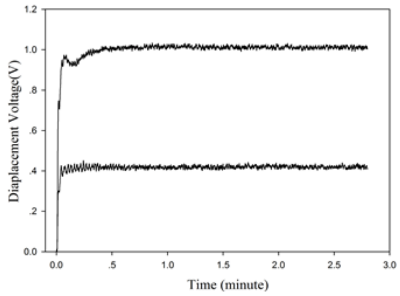


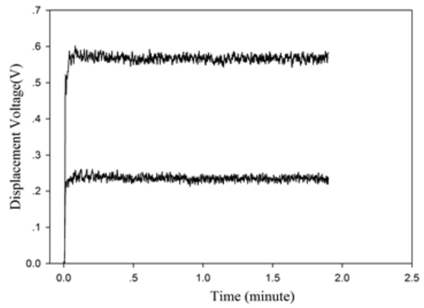
FIGURE 14 Dynamic measurements of the AD698 measurement circuit for proportional valve

5.2 DYNAMIC TEST OF OPENING OF HYDRAULIC VALVE

Valvistor hydraulic cartridge valve is internally provided with a hydraulic flow - position feedback mechanism, which achieves a continuous proportional control of the main valve displacement through controlling the flow of the pilot valve. In this hydraulic system, throttle valve and fixed differential reducing valve form proportional velocity regulating valve. It achieves the monotone control of the flow by input voltage signal. Experiments test the open-loop dynamic step response of proportional throttle valve of this system. The curve in Figure 16 is the open-loop step response characteristic of the main spool displacement.



a)



b)

FIGURE 15 Open-loop step response characteristic of main spool displacement

Figure 15a is shown that 3MPa pressure applies to the system, and the displacement of the main valve should be given 0.3mm and 0.8mm respectively. Y-axis represents the voltage value corresponding to the spool displacement, which measures by AD698 circuit of the inductance sensor. In Figure 15b, system pressure is 10MPa, and the displacement is 0.2mm and 0.4mm respectively.

The above experimental testing curves show that:

- when the pressure of the hydraulic system increases, the dynamic response speed of the main valve is also acelerated;
- when the pressure of the system can be certain, the time that the main spool reaches the given displacement is also increased with the increases of the opening displacement of the main spool;
- the dynamic response characteristic of the spool is very stable, without overshoot and oscillation.

The curves of the main valve's displacement voltage and the flow rate is shown in Figure 16. When system pressure is 10Mpa, and when the input voltage signal of the main valve is in fixed number of 4V, the opening of the valve is 0.4mm corresponding to this voltage. The flow rate increases progressively with enlargement of the main valve's the opening displacement. The valve has good characteristics of control accuracy and dynamic response.

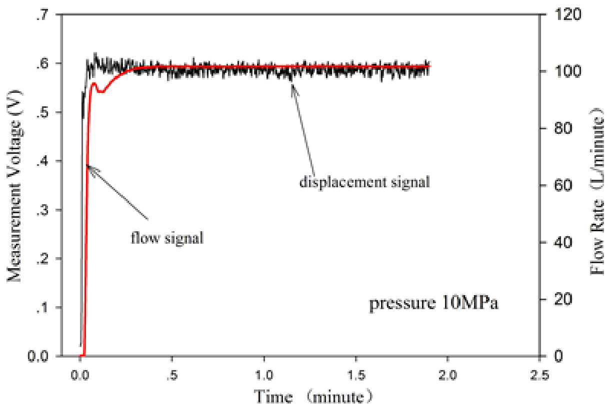


FIGURE 16 Relationship between displacement voltage and flow rate of main spool

6 Conclusions

The results of the experimental test of the sensor measurement circuit for hydraulic proportional control valve show as following.

- The three coil differential solenoid type inductive sensor can improve the output characteristics of the sensor in linear range. The linearity becomes better.
- Compared with the half-wave rectifier circuit, AD698 measuring circuit has a better linearity and repeatability when the valve works at static. And the hysteresis is low as the same.
- Under conditions of ensuing measurement range, the circuit designed to improve the sensitivity of the AD698 measurement circuit does work as desired.
- When the valve moves without hydraulic system, the results of the dynamic circuit measurement is found that the AD698 measures the valve movement has good linearity and fast response. And the half-wave rectifier circuit has a nonlinear region, in which both circuits can be used to detect the displacement of proportional valve. When the measurement requirements are higher, the circuit using AD698 can achieve real-time accurate measurement better.
- Given the main valve a certain voltage value, the spool has an opening displacement corresponding to the valve. The greater the system pressure, the faster the response speed of the main valve. AD698 measuring circuit can test the dynamic measurement of the hydraulic system in real time with a good effect.
- In addition, both type of the sensor detection circuits can be applied to micro vibration signal measurement and non-power electrical measurement system, etc.

Acknowledgments

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