Electronics, Communications and Networks
A.J. Tallón-Ballesteros et al. (Eds.)

doi:10.3233/FAIA231204

Development of a High Precision Instrument for Strain Sensors

Jian XU[1], Yizhi ZHANG, Haifeng QIN and Kexing CHEN
Changcheng Institute of Metrology and Measurement, Beijing 100095, China

Abstract. This paper introduces the design of a high-precision instrument for strain sensors, which accuracy class is 0.0005. In order to reach that high accuracy AC excitation voltage with 225Hz frequency, pulse width modulation multi-slope integration and high-precision voltage reference are developed. To verify the consistency of the measurement accuracy and uncertainty of the instrument, the comparison test of the DMP9000H high-precision instrument and the DMP41 high-precision instrument (made by HBM Germany) is carried out in two research institutions, the comparison results show that the relative deviation between DMP9000H and DMP41 measured at the comparison point is within ± 0.0005%, and the relative expanded uncertainty of DMP9000H measured at the comparison point is 1.0 × 10-5 (k=2); $|E_n|$of the measurement results of each comparison point are less than 0.5, which indicates that the difference between DMP9000H and DMP41 is within reasonable expectation, and the comparison result is satisfied.

Keywords. Strain sensor, high-precision, instrument, comparison test

1. Introduction

The measurement of force and torque is not only applied in traditional industries such as industry, agriculture, processing and manufacturing, metallurgy and petroleum, but also widely used in modern scientific research, aerospace, highway bridges and construction processes, such as soil stress [1], overload protection of highway bridges [2], engine torque and thrust test[3-6], etc. The method for measuring force and torque is to attach a strain gauge to a metal elastomer, the change of the resistance of the strain gauge is proportional to the force or torque. The high-precision measurement of force and torque also reflects the force measurement level of a country or region. At present, the measurement accuracy of the DMP41 high-precision digital measuring instrument of HBM company can reach 0.0005, which is the highest accuracy class in the world and is widely used for international comparison and high-precision measurement of force and torque. Domestic researches have been done to improve the measurement accuracy of instruments, and the ratio measurement technology [7] and six-wire compensation technology [8] have been proposed. The design principle of a high-precision instrument is different from the DMP41 made in German and the design principle are introduced in this paper in detail, and the measurement accuracy of the instrument is verified by the comparison test with DMP41.

[1] Corresponding Author: Jian XU, Changcheng Institute of Metrology and Measurement, Beijing 100095, China; E-mail: ship321@sina.com.

2. Key technologies

2.1. AC excitation bridge supply

AC excitation bridge supply is one of the most effective methods to improve the measurement accuracy of the instrument, for the various error sources in the circuit such as thermal noise, power-line interference can be suppressed by AC excitation circuit. The AC waveform with frequency of 225Hz is formed by sending fixed frequency signal to D/A by MCU. After capacitance shaping, the AC waveform can be output to the drive amplifier circuit to generate the final 225Hz excitation waveform. The circuit diagram of waveform generation is shown in Figure 1.

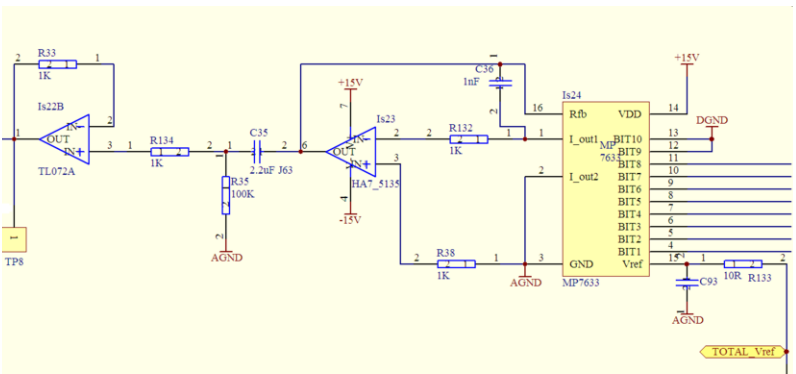

Figure 1. The circuit diagram of AC voltage excitation.

The strain senor with external 350 Ω resistance is driven by 225Hz AC excitation , the current output of ordinary amplifier is generally small, and it is difficult to drive the 350 Ω resistance, which will cause the drop of driving voltage, and seriously damage of the driving amplifier. Therefore, the push-pull transistor current expansion mode is used to increase the driving capacity. The circuit diagram is shown in Figure 2.

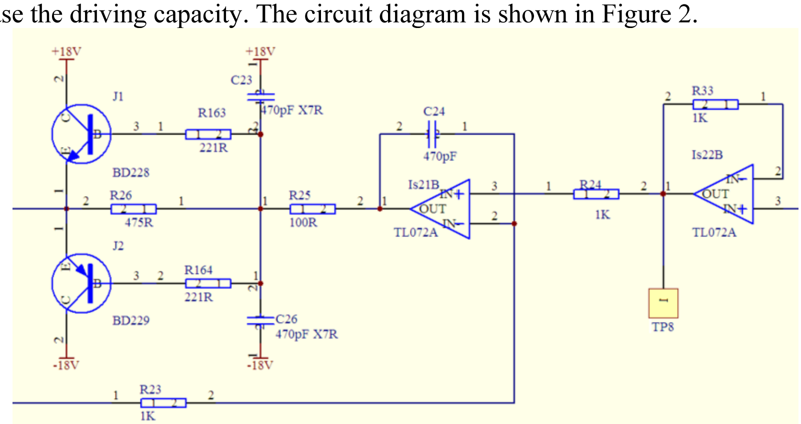

Figure 2. 225Hz AC excitation drive circuit.

2.2. Pulse width modulation multi-slope integration

Pulse width modulation multi-slope integration provides a compensated square pulse signal wave, which converts the oblique straight line signal with positive slope into a continuous triangular wave signal, as shown in Figure 3.

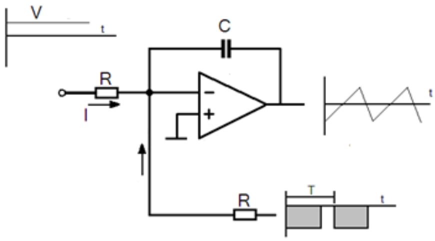

Figure 3. The diagram of multi-slope integration transforming input signal into triangular wave signal.

A triangular wave signal is formed by input measurement signal V and the input square wave pulse signal is formed by an integrator composed of amplifiers. The comparator is needed to obtain the digital quantity of the input signal represented by the triangle wave, though the input measurement signal V has a proportional relationship with the compensated square wave pulse signal, the controller cannot obtain the quantity of the input signal directly. The output square wave signal formed by comparator is the comparison results by standard triangular wave signal generated by square wave signal and the triangular wave signal generated by the input signal, as shown in Figure 4.

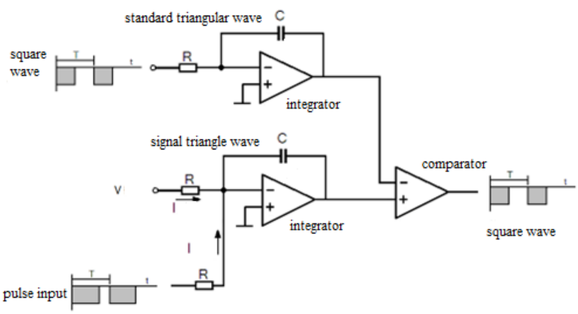

Figure 4. The diagram of multi-slope integration technology.

The two triangle waves have the same period, the standard triangle wave has a larger amplitude than the signal triangle wave. At the same time, it is input into the comparator, and the comparator outputs the corresponding square wave signal. The standard triangular wave and the signal triangular wave are input into the comparison amplifier at the same time. When the input signal is 0V, the signal triangular wave is isosceles triangular wave. After comparing with the standard triangular wave, the square wave with 1:1 duty ratio is output. A square wave without 1:1 duty ratio is generated by the triangle wave of the positive and negative full-range signal compared with the standard triangle wave, as shown in Figure 5. The output square wave signal is input into the MCU, the square wave pulse width can be easily obtained by a counter. The pulse width represents the size of the input signal. The size of the pulse width can be calculated by the MCU to obtain the digital results of the input signal. The actual schematic circuit diagram is shown in Figure 6.

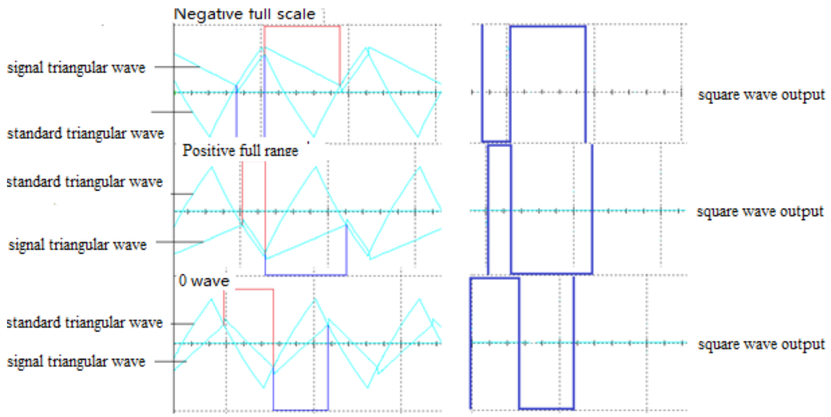

Figure 5. Comparison of output square wave.

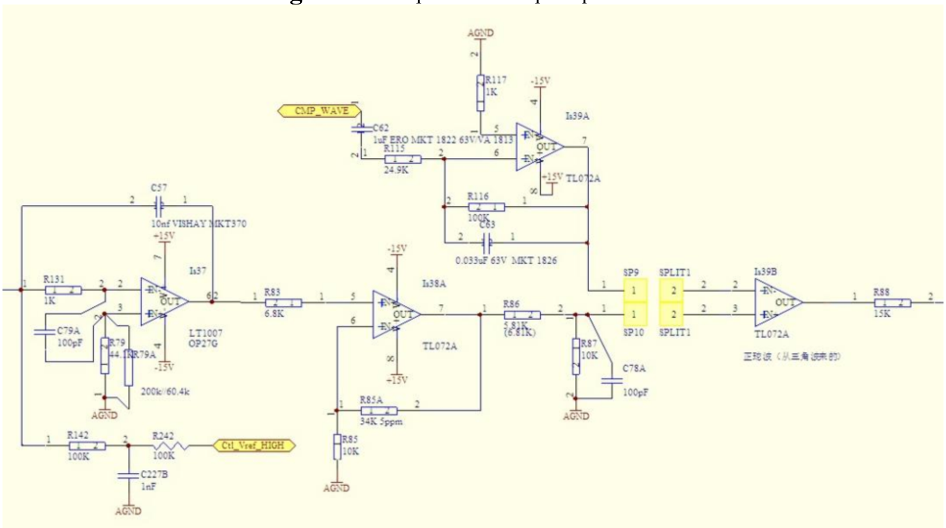

Figure 6. Schematic diagram of pulse width modulation circuit.

2.3. Design of high-precision voltage reference

The standard reference source voltage for the analog-to-digital conversion is provided by the reference circuit. The basic principle of analog-to-digital conversion is comparison. The comparison between the internal standard reference source of the instrument and the external input voltage signal is to get a digital result displayed on the instrument screen in the form of voltage. The accuracy, temperature drift, annual drift stability, linearity and other technical parameters of the voltage reference module directly affect the measurement accuracy and stability of the instrument. The parallel connection of the resistances is adopted to decrease the noise of the high-precision reference source. First, the temperature coefficients of resistances are tested and matched. The resistances with a temperature coefficient of - 1ppm/°C are recorded as n1.0, and the resistances with a temperature coefficient of+1ppm/°C are recorded as p1.0. The very stable 10kΩ resistance (<0.25×10-6/℃) can be got by this method. Figure 7 is a partial circuit diagram of a high-precision voltage reference source.

3. Comparison test

A comparative test was carried out at National Institute of Measurement and Testing Technology (referred to as Institute 1) and Changcheng Institute of Metrology and Measurement (referred to as Institute 2). The DMP9000H instrument for strain sensor was compared with the DMP41 high-precision digital measuring instrument made by German HBM company.

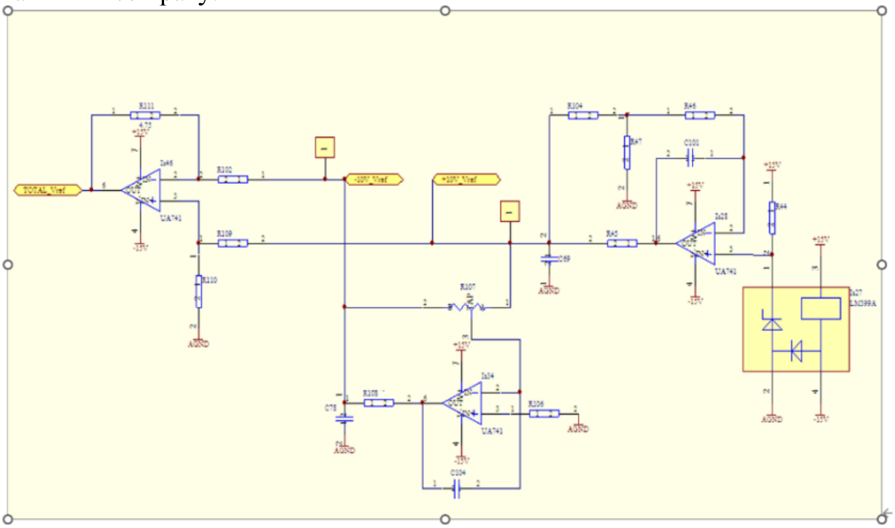

Figure 7 Partial circuit diagram of high-precision voltage reference source.

The transfer standard for comparison was the K148 high-precision full-bridge calibrator made by German HBM company. The comparison method was to evaluate the consistency of the two instruments by comparing DMP41 and DMP9000H on the same indication value of K148[9-11].

3.1. Comparison instrument and transfer standard

The information related to the comparison instruments and transfer standards is listed in Table 1.

Table 1. Parameters of DMP41, DMP9000H and K148 for comparison

Name	Number (Institute 1)	Number (Institute 2)	Range (mV/V)	Accuracy class
DMP9000H	202208190001	202208190001	(0 -2.5)	0.0005%
DMP41	819192501	839491501	(0 -10)	0.0005%
K148	0143	0351	(0.1 -100)	0.0025%

3.2. Comparison data

Eight calibration points of 0, 0.4, 0.6, 0.8, 1.0, 1.4, 1.8 and 2.0 mV/V are selected for comparison, the excitation voltage is 5 V, and the test room temperature is 23 °C. The channel 1 of DMP41 and DMP9000H are measured for three times. The test data of the Institute 1 are shown in Table 2 and Table 3 respectively. The test data of the Institute 2 are shown in Table 4 and Table 5 respectively.

Table 2. DMP41/819192501 channel 1 test data (Institute 1)

mV/V	**test1**	**test2**	**test3**	**average**
0	0	0	0	0
0.4	0.399980	0.399981	0.399981	0.399981
0.6	0.599989	0.599989	0.599989	0.599989
0.8	0.799980	0.799981	0.799981	0.799981
1.0	0.999973	0.999973	0.999973	0.999973
1.4	1.399967	1.399968	1.399968	1.399968
1.8	1.799961	1.799963	1.799962	1.799962
2.0	1.999962	1.999961	1.999962	1.999962
0	0.000001	0.000001	0.000001	0.000001
0	0	0	0	0
-0.4	-0.399982	-0.399982	-0.399982	-0.399982
-0.6	-0.599988	-0.599989	-0.599989	-0.599988
-0.8	-0.799979	-0.799980	-0.799980	-0.799980
-1.0	-0.999971	-0.999972	-0.999972	-0.999972
-1.4	-1.399965	-1.399965	-1.399965	-1.399965
-1.8	-1.799960	-1.799959	-1.799960	-1.799960
-2.0	-1.999960	-1.999960	-1.999960	-1.999960
0	0.000001	0.000001	0.000001	0.000001

Table 3. Test data of DMP9000H high-precision measuring instrument (Institute 1)

mV/V	test1	test2	test3	average
0	0	0	0	0
0.4	0.399980	0.399980	0.399980	0.399980
0.6	0.599989	0.599988	0.599989	0.599989
0.8	0.799981	0.799980	0.799981	0.799981
1.0	0.999973	0.999972	0.999973	0.999973
1.4	1.399967	1.399968	1.399968	1.399968
1.8	1.799960	1.799961	1.799961	1.799961
2.0	1.999960	1.999960	1.999960	1.999960
0	0.000001	0.000001	0.000001	0.000001
0	0	0	0	0
-0.4	-0.399982	-0.399981	-0.399982	-0.399982
-0.6	-0.599989	-0.599988	-0.599988	-0.599988
-0.8	-0.799979	-0.799979	-0.799980	-0.799979
-1.0	-0.999972	-0.999971	-0.999972	-0.999972
-1.4	-1.399964	-1.399964	-1.399964	-1.399964
-1.8	-1.799961	-1.799958	-1.799959	-1.799959
-2.0	-1.999960	-1.999958	-1.999959	-1.999959
0	0.000001	0.000001	0.000001	0.000001

Table 4. DMP41/839491501 by channel 1 test data (Institute 2)

mV/V	test1	test2	test3	average
0	0	0	0	0
0.4	0.399980	0.399980	0.399981	0.399980
0.6	0.599983	0.599983	0.599983	0.599983

mV/V	test1	test2	test3	average
0.8	0.799966	0.799967	0.799967	0.799967
1.0	0.999967	0.999967	0.999967	0.999967
1.4	1.399963	1.399963	1.399964	1.399963
1.8	1.799961	1.799961	1.799962	1.799961
2.0	1.999967	1.999967	1.999966	1.999967
0	0	0	0	0
0	0	0	0	0
-0.4	-0.399981	-0.399981	-0.399981	-0.399981
-0.6	-0.599982	-0.599982	-0.599983	-0.599982
-0.8	-0.799969	-0.799970	-0.799970	-0.799970
-1.0	-0.999966	-0.999967	-0.999967	-0.999967
-1.4	-1.399965	-1.399965	-1.399965	-1.399965
-1.8	-1.799960	-1.799959	-1.799960	-1.799960
-2.0	-1.999965	-1.999964	-1.999963	-1.999964
0	0	0	0	0

Table 5. Test data of DMP9000H high-precision measuring instrument (Institute 2)

mV/V	test1	test2	test3	average
0	0	0	0	0
0.4	0.399981	0.399981	0.399981	0.399981
0.6	0.599982	0.599982	0.599983	0.599982
0.8	0.799967	0.799967	0.799967	0.799967
1.0	0.999966	0.999966	0.999967	0.999966
1.4	1.399964	1.399964	1.399964	1.399964
1.8	1.799961	1.799961	1.799961	1.799961
2.0	1.999968	1.999968	1.999967	1.999968
0	0	0	0	0
0	0	0	0	0
-0.4	-0.399981	-0.399981	-0.399982	-0.399981
-0.6	-0.599982	-0.599982	-0.599982	-0.599982
-0.8	-0.799969	-0.799968	-0.799968	-0.799968
-1.0	-0.999966	-0.999967	-0.999967	-0.999967
-1.4	-1.399964	-1.399964	-1.399964	-1.399964
-1.8	-1.799961	-1.799961	-1.799960	-1.799961
-2.0	-1.999965	-1.999966	-1.999966	-1.999966
0	0	0	0	0

4 Uncertainty evaluation

4.1 Combined uncertainty

Four factors affecting the combined uncertainty of DMP41 and DMP9000H, they are the accuracy of K148, the measurement accuracy of 0.0025% given by the official, the repeatability of the measurement results, the resolution, and the influence of temperature change. The zero return difference is a fixed value, it is subtracted during calculation, so the influence of return-to-zero is omitted. The combined uncertainty table is given in Table 6.

Table 6. List of DMP41 indication uncertainty components

Number	influence factor	Evaluation method	Distribution	Standard uncertainty component u_i
1	accuracy of K148:U_{mac}	B	Normal distribution，k=2	$u_{mac} = U_{mac}/2$
2	Repeatability:R_{ep}	A	/	$u_{rep} = \frac{1}{\overline{x_i}}\sqrt{\frac{\sum_{i=1}^{3}(x_i - \overline{x_i})^2}{3 \times (3-1)}}$
3	Resolution:R_{es}	B	Uniform distribution	$u_{res} = R_{es}/(\overline{x_i} \cdot 2\sqrt{3})$
4	influence of temperature:T_{tem}	B	Uniform distribution	$u_{tem} = S_t \cdot \Delta_t/(2\sqrt{3} \cdot \overline{x_i})$

x_i—measurement value; $\overline{x_i}$— average;R_{res}— resolution; S_t— temperature coefficient Δ_t— temperature change.

During the test, the temperature change in the Institute 1 was 0.6 °C, in institute2 is 0.7 °C. The temperature effect of K148 is 0.0025% mV/V/K. The combined uncertainty of the instrument is calculated according to the following formula, and the results are shown in Table 7.

$$u_c = \sqrt{u_{mac}^2 + u_{rep}^2 + u_{res}^2 + u_{tem}^2}$$

Table 7 Composite standard uncertainty of DMP41 and DMP9000H

Standard value	Institute 1		Institute 2	
	u_{c41}	u_{c9000H}	u_{c41}	u_{c9000H}
0.4	0.000271%	0.000271%	0.000283%	0.000283%
0.6	0.000260%	0.000261%	0.000264%	0.000264%
0.8	0.000260%	0.000256%	0.000258%	0.000258%
1.0	0.000254%	0.000254%	0.000255%	0.000255%
1.4	0.000252%	0.000252%	0.000253%	0.000253%
1.8	0.000251%	0.000251%	0.000252%	0.000252%
2.0	0.000251%	0.000251%	0.000251%	0.000251%
-0.4	0.000273%	0.000274%	0.000282%	0.000282%
-0.6	0.000261%	0.000261%	0.000264%	0.000264%
-0.8	0.000260%	0.000256%	0.000258%	0.000258%
-1.0	0.000254%	0.000254%	0.000255%	0.000255%
-1.4	0.000252%	0.000252%	0.000253%	0.000253%
-1.8	0.000251%	0.000251%	0.000252%	0.000252%
-2.0	0.000251%	0.000251%	0.000251%	0.000251%

4.2 Expanded uncertainty

The relative expanded uncertainty of the instrument is calculated as follows:
$U_c = k \times u_c$
Where, the coverage factor is k=2, and the confidence probability is about 95%.

4.3 Consistency of comparison results

According to the evaluation of measurement uncertainty in JJF1059-2012, the consistency of comparison results is evaluated by E_{n} values, which is calculated according to the following formula:

$$E_n = \frac{\delta_r}{\sqrt{U_{c41}^2 + U_{c9000H}^2}}$$

δ_r - relative deviation of indication of comparison results:

$\delta_r = \frac{x_l - x_p}{x_p}$

x_l,x_p - the relative expanded uncertainty of DMP9000H and DMP41 respectively (k=2).

According to the evaluation of measurement uncertainty in JJF1059-2012, the criterion for the value to meet the requirements is: E_n<1.The consistency (value) of comparison results is shown in Table 8.

Table 8 Consistency of comparison results（E_n）

Standard value	Institute 1		Institute 2	
	δ_r	E_n	δ_r	E_n
0.4	-0.00025%	-0.65	0.00025%	0.62
0.6	0	0	-0.00017%	-0.45
0.8	0	0	0	0
1.0	0	0	-0.00010%	-0.28
1.4	0	0		0.20
1.8	-0.00006%	-0.16	0	0
2.0	-0.00010%	-0.28	-0.00005%	0.14
-0.4	0	0	0	0
-0.6	0	0	0	0
-0.8	-0.00013%	-0.34	-0.00025%	-0.69
-1.0	0	0	0	0
-1.4	-0.00007%	-0.20	0.00007%	-0.20
-1.8	-0.00006%	0.16	0.00006%	0.16
-2.0	-0.00005%	-0.14	0.00010%	0.28

5 Conclusion

The design of a high-precision instrument for strain sensor is introduced. In order to verify the measuring accuracy of the instrument, comparative tests are carried out at National Institute of Measurement and Testing Technology and Changcheng Institute of Metrology and Measurement. The method of comparison with DMP41 instrument is adopted to verify the measurement accuracy of the new-developed instrument. The comparison results show that:

1. The relative deviation between the DMP9000H and the DMP41 at the comparison point is within ± 0.0005%, and the relative expanded uncertainty is 1.0 × Within 10-5 (k=2).

2. The measurement values of DMP9000H and DMP41 are less than 0.5, indicating that the difference between DMP9000H and DMP41 is within reasonable expectations, and the comparison results are satisfied.

References

[1] Yu Huayue, Li Shunqun, Liu Chengzhi. Stress Expression and Test Instrument Development in Axisymmetric State [J] China Test, 2022, 48 (8): 53-59.

[2] Lv Qiong, Zhang Chunfa, He Zhiang, et al. Research on Bridge SS-steel Guardrail Structure Based on OverLoad Protection Function [J]. Highway. 2020,65 (7): 164-166.

[3] Wang Zefeng, Kou Fujun. Research on the Measurement Principle of Helicopter Main Rotor Torque [J]. China Test. 2020, 46 (9): 47-52.

[4] Qin Haifeng, Liu Sibo, Liu Yonglu. Technical Characteristics Analysis of Force Sensor under Engine Thrust Test Conditions [J] Measurement and Control Technology. 2021,40 (2): 74-79.
[5] Zhang Lei She, Hu Qing. Experimental Study on Thrust Characteristics of Solid Rocket Motor Under Water [J]. Energetic Materials. 2020, 28 (12): 1184-1189
[6] Liu Wanlong, Wang Dezhi, Liu Shuo, et al. Thrust Vector Measurement of Several Foreign Rocket Engines Device overview [J] Rocket Propulsion 2021,47(4):6-12.
[7] Jiang Dijiao.An Low Pass Filter Circuit Using 4580 Amplifiers:China,201520612568.9[P].2015-08-14.
[8] Zhang Zhenjie. Six-Wire System in Strain Bridge Measuring Circuit [J]. Strength and Environment. 1992, 19 (01): 54-58
[9] JJF1117-2010, Specification for Comparison of Measuring Instruments [S]. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, China National Standardization Administration, 2010.
[10] JJF1059-2012 Evaluation and Expression of Measurement Uncertainty [S]. General Administration of Quality Supervision, Inspection and Quarantine, 2012.
[11] JJG1469-2014 Calibration Specification for Strain Sensor Measuring Instrument [S]. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2014.