Research on measuring time constant of NANMAC thermocouple

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Abstract: The theory for measuring the time constant of thermocouple was introduced, and the method for measuring the time constant of NANMAC thermocouple by using dynamic calibration system of transient surface temperature sensor was proposed. In this system, static and dynamic calibrations were conducted for infrared detectors and thermocouples, and then both temperature-time curves were obtained. Since the frequency response of infrared detector is superior to that of calibrated thermocouple, the values measured by infrared detectors are taken as true values. Through dividing the values measured with thermocouples by those with infrared detectors, a normalized curve was obtained, based on which the time constant of thermocouple was measured. With this method, the experiments were carried out with NANMAC thermocouple to obtain its time constant. The results show that the method for measuring the time constant is feasible and the dynamic calibration of thermocouples can be achieved at microsecond and millisecond level. This research has a certain reference value for research and application of NANMAC thermocouple temperature sensor.

Key words: thermocouple; time constant; static calibration; dynamic calibration; normalized curve

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During temperature measurement, when the heat exchange between the thermocouple temperature sensor and the measured object achieves a dynamic equilibrium, the temperature on measuring end of thermocouple is taken as the measured temperature. However, there is a difference between the measured temperature and the actual temperature, i.e., so-called dynamic response errors, due to the thermal inertia and limited thermal conductivity of the temperature sensor thermal devices in this process[1]. To reduce this dynamic error, it is necessary to study the dynamic response characteristics of thermocouple temperature sensor measured by an important indicator, i.e. time constant. When the temperature step applied to calibrated thermocouple is given, the dynamic response error value of thermocouple only depends on time constant, τ. Therefore, determination of the time constant of temperature sensor is of great significance.

Different areas and industries have different requirements for the time constant of thermocouple due to many complex factors. But it is difficult to obtain accurate value only by theoretical calculation. Thus, experimental measurement methods are employed in practice, among which temperature step method is most commonly used. Generally, the measuring end of thermocouple is heated by quasi-step laser, and then a temperature curve of thermal equilibrium state is obtained from measuring end, based on which a method for measuring the time constant of thermocouple is finally acquired[2]. However, it is difficult to obtain a curve with first-order system characteristics for time constant of NANMAC thermocouple measured with this method. Hence, research on the method of accurately measuring the time constant of NANMAC thermocouple is a very valuable job.

In this paper, dynamic response curves of infrared detectors and calibrated thermocouple are obtained by using dynamic calibration system of surface temperature sensor. Since the frequency response of infrared detector is superior to that of calibrated thermocouple, the values measured by infrared detectors are taken as the true values. The true values and those measured by the calibrated sensor are normalized to get a curve with first-order system characteristics. Based on the normalized curve, the method for measuring the time constant of thermocouple is acquired.

1 Theoretical analysis of the time constant of thermocouple

For thermocouple temperature sensors, the time constant τ can be expressed as

$$\tau = \frac{WVC}{hA}, \tag{1}$$

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where W is the proportion of the thermocouple material; V, volume; C, specific heat; h, heat conductivity coefficient; A, the area of fluid film surrounding thermocouple[3]. WVC represents thermal capacity at measuring nodes and hA is the rate of heat transfer to measuring contacts of the thermocouple. It can be seen from Eq. (1) that the time constant of thermocouple is affected by thermocouple material, structural style temperature environment, etc. Therefore, it is difficult to compute time constant from empirical formula and experimental methods are usually employed in practice. As for the dynamic response of temperature sensor, energy balance equation for thermocouple is obtained by assuming that temperature distribution inside the thermocouple sensor, conduction and radiation heat transfer of sensor are negligible according to the traditional model. Based on energy balance equation, thermocouple response to step temperature as a first-order linear system can be acquired. Its expression is

$$T - T_0 = (T_e - T_0)(1 - e^{-t/\tau}), \qquad (2)$$

where T is the indication temperature on thermocouple; T_0, the initial temperature of the hot junction; T_e, the step temperature; t, the response time to step temperature; τ, the time constant of thermocouple. When $t = \tau$,

$$T - T_0 = (T_e - T_0)(1 - e^{-1}). \qquad (3)$$

According to Eq. (3), time constant τ is defined as the difference between the indication temperature on thermocouple, T, and the initial temperature, T_0. The time required for time constant τ reaching 63.2% of temperature step ($T_e - T_0$) is shown in Fig. 1[4].

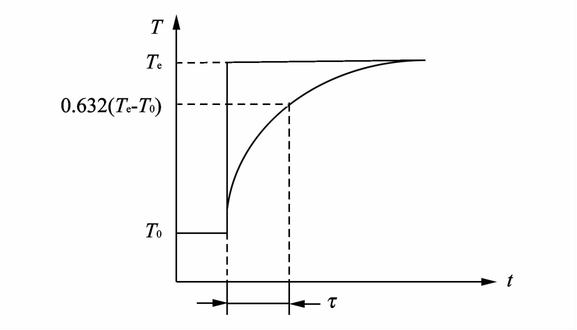

Fig. 1 Dynamic response curve of temperature sensor

2 Method for measuring the time constant of thermocouple

In order to obtain the time constant of NANMAC thermocouple, a traceable dynamic calibration system of transient surface temperature sensors was adopted, as shown in Fig. 2. On the basis of which the temperature-time curves of infrared detector and thermocouple were obtained. The values measured by infrared detectors were taken as true values. The true values and values measured by the calibrated sensor were normalized to get a curve, and then the time constant of thermocouple was obtained according to the definition of time constant[5].

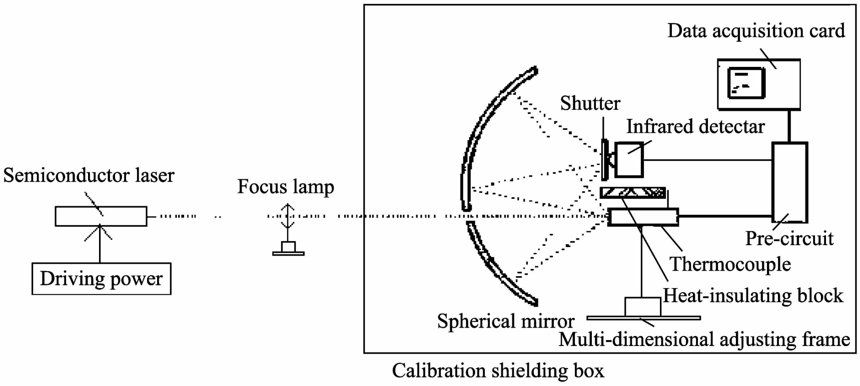

Fig. 2 Dynamic calibration system

This dynamic calibration system adopts controllable single-pulse lasers emitted by a high-power semiconductor laser with faster rise time as dynamic excitation signal. The semiconductor laser has a divergence angle and can not take full advantage of the energy of laser, therefore, a laser focus lamp is put before the laser to cause an instant temperature rise on the surface of the calibrated thermocouple which is on one conjugate focus of the spherical mirror. Then thermocouple produces heat conduction and thermal radiation, and thermal radiation through the spherical mirror focuses on infrared detector on the other conjugate focus. Heat sources are measured simultaneously by infrared detector and thermocouple, and the frequency response of infrared detector is superior to that of calibrated temperature sensor due to the fact that the photonic device selected is photoconductive Hg-Cd-Te infrared detector whose time constant is less than 10. Thus, the former values are taken as the true values to calibrate the latter to get dynamic error and then dynamic compensation is carried on[6].

2.1 Static calibration of infrared detector

The infrared detector and calibrated thermocouple were placed at the two conjugate focuses of spherical mirror. High-power semiconductor laser emitted single pulse laser whose pulse width can be modulated. The single pulse laser xposed to the calibrated surface temperature sensor through the hole generating a temperature rise on the surface. The temperature change was shown as the voltage value on the digital capture card, based on which the temperature value at this time can be obtained through looking up the corresponding indexing table. Meanwhile the infrared thermal radiation emitted by the calibrated surface temperature sensor focused on the HgCdTe infrared detector through spherical mirror. When the calibrated sensor reached thermal equilibrium, the shutter was quickly opened and closed to make infrared detector receive radiation focus signal at the moment of opening the shutter. The output voltage amplitude of infrared detectors corresponding to the temperature was read through opening the shutter, and then the laser power was gradually increased. Multi-group output voltage amplitudes of different temperatures were obtained by repeating the above operations. Based on the nonlinear fitting of the multiple sets of data, a corresponding relationship curve between the output voltages of infrared detector and the temperatures was obtained, and then static calibration for infrared detector was achieved by values transfer[7].

2.2 Dynamic calibration of infrared detector and calibrated thermocouple

The current knob of high-power semiconductor lasers was adjusted to change its power and the signal pulse width was set to control the light time, and then a quasi-step change in temperature was generated. The heat generated by the pulse laser made the calibrated sensor rapidly warm and emit infrared thermal radiation at the same time, which focused an image through spherical mirror. Meanwhile, a corresponding temperature change was generated by the infrared detector at another conjugate focus of the spherical mirror. The output signals of calibrated sensor and infrared detector were recorded by a data acquisition card and then voltage-time (V-T) curve at this temperature was obtained. Finally, the corresponding temperature-time (T-t) curve can be acquired according to voltage-temperature (V-T) and voltage-time (V-t) curves of calibrated sensor and infrared detector.

2.3 Normalization processing

Based on the dynamic calibration for the temperature-time curves of calibrated sensor and infrared detector, since the frequency response of infrared detector is superior to that of calibrated sensor, the sensor was heated by laser emitting infrared heat radiation which was received by the infrared detector. At the beginning, the rising curve of infrared detectors was faster than that of calibrated sensor. When reaching a certain moment, both curves rose together and a certain temperature difference existed between them. In this case, the temperatures measured by infrared detector and thermocouple were approximately equal, thus, thermocouple was considered to reach a thermal equilibrium. The values of infrared detectors were taken as 100% of the values, and then normalization processing was conducted on the values measured by thermocouple. Finally, the time constant of the thermocouple can be determined according to the definition for the time constant of temperature sensos.

3 Results and analysis

The knob of semiconductor laser was adjusted to set the current 20 A, namely power 150 W, and set the signal pulse width 40 ms. Dynamic calibration was carried out with infrared detector and calibrated thermocouple and then V-t curve was obtained by using data acquisition card. According to the static calibration curve of the former and indexing table of the latter, the temperature-time curves of infrared detector and calibrated thermocouple at this temperature can be obtained, as shown in Fig. 3.

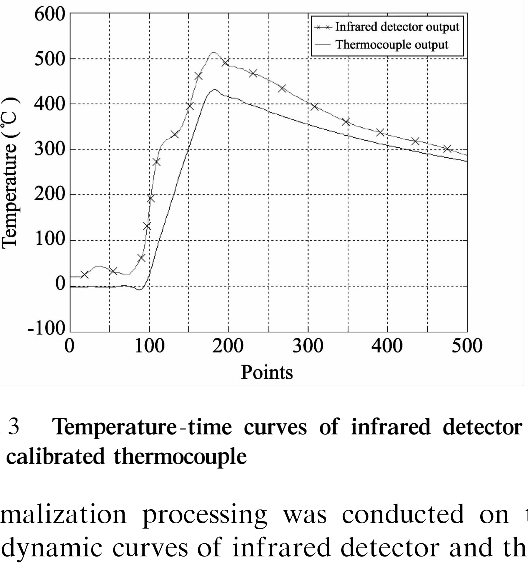

Fig. 3 Temperature-time curves of infrared detector and calibrated thermocouple

Normalization processing was conducted on the above dynamic curves of infrared detector and thermocouple, and the result is shown in Fig. 4, from which it can be known that the time constant of thermocouple is 18 ms.

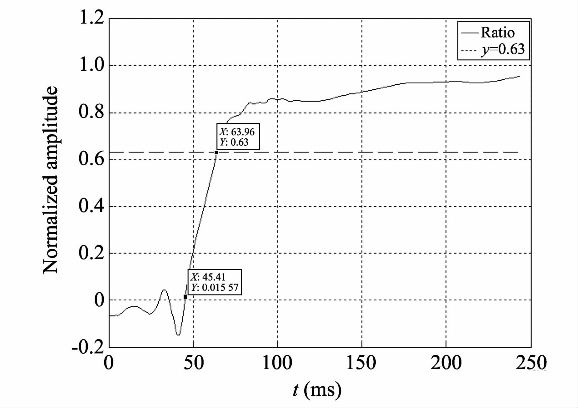

Fig.4 Normalization result

The time constants of NANMAC thermocouple under different currents and pulse widths were determined through adjusting the current pulse width of semiconductor laser, as shown in Table 1.

Table 1 Time constant

Current (A)	Pulse width (ms)	Time constant (ms)
20	40	18
20	30	20
25	30	20

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基于 NANMAC 热电偶的时间常数测试技术研究

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摘 要： 本文介绍了热电偶时间常数的测试理论，提出了运用瞬态表面温度传感器动态校准系统实现对NANMAC 热电偶时间常数的测试方法。该系统对红外探测器和热电偶进行了静态校准和动态校准，得到两者的温度-时间曲线。由于红外探测器的频率响应优于被校准热电偶的频率响应，因此，以红外探测器测得的值作为真值，用热电偶测得的值与红外探测器测得的值相比得到一条归一化的曲线，并由归一化曲线求得热电偶的时间常数。利用该方法对 NANMAC 热电偶进行时间常数的测试实验，得到了该热电偶的时间常数。实验结果表明：该时间常数测试方法是可行的，可以实现对微秒、毫秒量级热电偶的动态校准，这对于 NANMAC 热电偶温度传感器的研究和应用具有一定的参考价值。

关键词： 热电偶；时间常数；静态校准；动态校准；归一化

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