Proceedings of the 2022 International Conference on Smart Manufacturing and Material Processing (SMMP2022), A. Nayyar (Ed.)

doi:10.3233/ATDE220835

Transient Quantitative Identification Algorithm Based on Laser Impulse Response

Xiaolong LIU, Jushang LI[1], Ruitong ZHANG, Hongjie JIANG, Xikuan CHEN, Jihao CHENG and Fucheng LIU
Changchun College of Electronic Technology, Changchun, Jilin 130013, China

Abstract. In order to improve the measurement accuracy of transient heat flow based on laser pulse response technology, a dynamic calibration algorithm of heat flow based on pulse response of fiber semiconductor laser is proposed. The system uses a high-power fiber semiconductor laser to generate modulated excitation, and quantitatively detects the transient heat flow energy in the form of pulsed radiation. The light intensity of the light source is adjusted by the homogenization of the light spot, and the energy measurement is completed with a Gardon meter. The data acquisition card and signal analysis circuit are used to realize the high-speed calculation and acquisition of the heat flow signal. Using the transient quantitative identification algorithm, the dynamic test performance of a circular foil heat flow meter of the GD series is tested and calibrated. The simulation analysis of the system's ability to modulate the signal verifies the feasibility of the system's light source modulation. A transient quantitative identification system based on high-power fiber semiconductor lasers is established in the experiment. The data curve noise after passing this algorithm is smaller and the accuracy is higher, which verifies the effectiveness of the algorithm. The algorithm can be applied to the field of rapid quantitative identification and analysis of transient heat flow energy.

Keywords. Fiber-optic semiconductor laser; Impulse response; Transient test; Quantitative identification

1 Introduction

Transient quantitative detection technology is used in many fields such as military and industry, among which the use of transient quantitative detection technology to complete heat flow sensing is an important research direction [1-5]. The calibration of the sensor is very important to improve the accuracy and reliability of the heat flow measurement results in the aerodynamic heat and thermal protection test and to standardize the heat flow measurement method [6]. The traditional heat flux density sensor is large in size and has a long response time.

D.S. Campbell et al. developed a thin film heat flow meter by analyzing the heat transfer theory of the sensor. The test shows that the response cutoff frequency of the thin film heat flow meter is 5.0kHz and the time constant is 10.0ms [7]. C.T. Kidd developed a zero-point calorimeter that meets the requirements of heat flow (90.8kW/cm^2) in

[1] Corresponding Author: Jushang LI, lijushang1984@163.com.

spacecraft reentry, and calibrated the sensor. The response time of the calibrated heat flow sensor is 3.5ms [8]. Holmberg D G, et al. developed a thin film heat sensor suitable for high flux environments. A sensor static and dynamic calibration system is built to calibrate the thin-film heat flow sensor. The cut-off frequency of the heat flow meter at 3.0dB is 3.0 kHz [9]. Stefan Lohle et al. proposed a dynamic calibration method using a noninteger identified system as a direct model. A Nd:YAG laser with a pulse width of 1ms was used as the heat flow source, and the zero-point calorimeter was dynamically calibrated to verify the correctness of the calibration method [10]. To solve the measurement problem of high heat flow sensors in the aviation and aerospace fields, Zhang Junqi et al. built a heat flow sensor calibration device based on high-power semiconductor lasers. The device uses the transfer calibration method to calibrate the American Gardon sensor at the heat flow value of 6.0-8.0MW/m2. The results show that the deviation of the calibrated sensor is within 3% [11]. Bai Qingxing et al. built a large-scale system consisting of a laser unit, a vacuum chamber and a standard heat flow sensor, aiming at the problems of low upper limit of heat flow (less than 2MW/m2) and inability to perform dynamic calibration of the current heat flow sensor calibration device using a high-temperature graphite plate as the heat flow source [12]. Luo Xiao et al. used vacuum evaporation coating technology to prepare a thin-film heat flow sensor that combines thermopile and thermocouple, which can simultaneously measure temperature and heat flow. The dynamic experimental results show that when the step heat flow value is 260W/m2, the response time of the sensor is 0.158s [13].

Aiming at the quantitative problem of heat flow in transient process, this paper proposes a data positive correlation classification algorithm based on laser impulse response, and constructs the transient quantitative relationship of heat flow from the continuity between data.

2 System Design

The dynamic calibration system consists of dynamic excitation signal source, calibrated sensor, signal conditioning circuit, transient data acquisition system and computer. The dynamic excitation signal source generates a transient excitation signal and acts on the calibrated sensor. The transient response in the form of voltage output by the sensor is amplified and filtered by the signal conditioning circuit, and then collected by the transient data acquisition system and sent to the computer for data analysis and processing, the sensor dynamic characteristic parameters are calculated by the relevant algorithm. Figure 2-1 shows the principle diagram of the dynamic calibration system for common excitation signals.

The type of dynamic excitation signal generator varies with the type of sensor being calibrated. The selection of dynamic signal generators is the key and difficult point in the construction of various dynamic test systems. Modern dynamic testing technology takes the computer as the core of the system, and the software written inside the computer coordinates the control of the entire system, and transmits the processed dynamic response curve and data of the sensor to the external computer through the external interface to complete storage, display and printing. Modern dynamic test system has the advantages of high degree of automation, high accuracy, multi-channel measurement and powerful system functions.

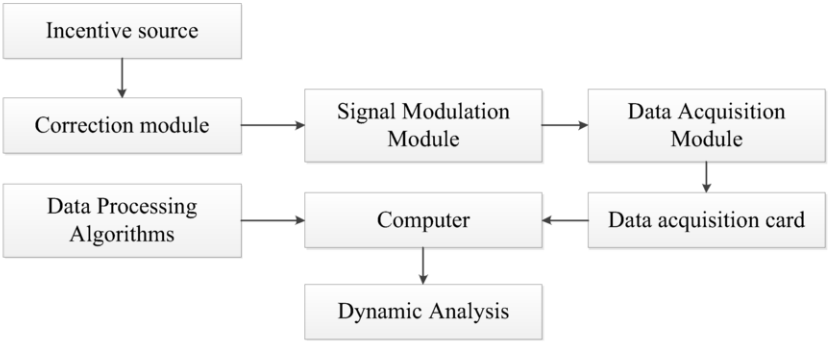


Fig 1. Transient quantitative identification system based on laser pulse response

The dynamic calibration system consists of dynamic excitation signal source, calibrated sensor, signal conditioning circuit, transient data acquisition system and computer. The dynamic excitation signal source generates a transient excitation signal and acts on the calibrated sensor. The transient response in the form of voltage output by the sensor is amplified and filtered by the signal conditioning circuit, and then collected by the transient data acquisition system and sent to the computer for data analysis and processing. , and the dynamic characteristic parameters of the sensor are calculated by the relevant algorithm, as shown in Fig. 1. The selection of dynamic signal generators is the key and difficult point in the construction of various dynamic test systems. Modern dynamic testing technology takes the computer as the core of the system, and the software written inside the computer coordinates and controls the entire system, and transmits the processed dynamic response curve and data of the sensor to the external computer through the external interface to complete storage.

3 Transient Quantitative Identification Algorithm

The response function of the unit pulse of the Gardon-type heat flow sensor is:

$$y(t) = \frac{1}{\tau} e^{-\frac{t}{\tau}} \tag{1}$$

where t is time and τ is the impulse response time constant.

This paper uses the Z-t function to complete the description of the heat flow characteristics. Let Z=ln[y(t)], then the fitting curve equation of Z-t curve can be expressed as:

$$Z = -\frac{t}{\tau} + \ln(\frac{1}{\tau}) \tag{2}$$

Meanwhile, the first-order impulse response time constant is:

$$\tau = -\frac{\Delta t}{\Delta Z} \tag{3}$$

Through the above method, the time constant of the sensor can be accurately calculated under the excitation of pulsed heat flow. The method can not only solve the calculation of the time constant under the step and pulse excitation of the heat flow sensor, but also can be applied to the calculation of the time constant of the first-order system similar to the thermocouple.

The constantan foil with thickness *S* and radius *R* is connected to a copper heat sink with the temperature.

Take a micro-element with radial thickness at radius *r*, and perform heat transfer analysis on δr. Under the condition of ignoring the heat loss on both sides of the circular foil and the internal temperature gradient, the temperature rise rate *v* of the micro-element ring is:

$$v = 2\pi r\delta r \cdot q - \frac{\partial T}{\partial r} \cdot k \cdot 2\pi rS + \left(\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \cdot \delta r \right) \cdot k \cdot 2\pi \left(r + \delta r \right) S \tag{4}$$

In the formula, is the temperature of the round foil at time and radius, c_ρ is the thermal conductivity of the constantan material, and is the specific heat capacity of the constantan material. Equation (4) can be simplified as:

$$\frac{c\rho}{k} \cdot \frac{\partial T}{\partial t} = \frac{q}{Sk} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} \tag{5}$$

Then the time constant after simplification is

$$\tau = \frac{R^2}{4\alpha} \tag{6}$$

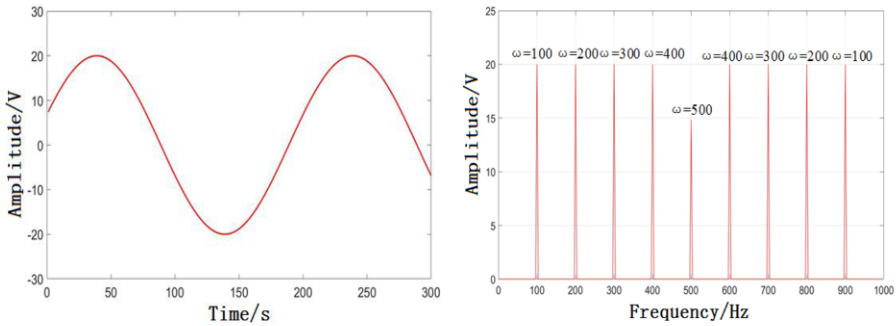
Where $\alpha = k/\rho c$ is the thermal diffusivity. The value α varies with the temperature. According to the Gardon meter copper wire brazing point and the working temperature characteristics of the constantan round foil material, take the thermal diffusivity of the constantan material as α=0.065cm2/s when the average temperature is 80 °C, we can get:

$$\tau = 3.7R^2 \tag{7}$$

The results show that the time constant of the Gardon meter is not only related to the thermal properties such as thermal conductivity and heat capacity, but also greatly affected by the radius of the constantan circular foil. The time constant is proportional to the square of the circular foil radius.

4 Modulation Parameters Simulation Analysis

The sinusoidal signal is selected as the dynamic excitation signal in the frequency domain, and the magnitude of the ordinate value of the spectral line depends on the magnitude of the spectral line amplitude of each frequency point. Manually adjust the frequency range to be tested, and the instrument automatically gives excitation signals of various frequencies within the set range point by point. The simulation analysis results are shown in Fig. 2.



(a) Sine function time domain signal (b) Sine function of different frequencies

Fig 2. Input signal time and frequency domain simulation

As shown in Fig. 2(a), the time domain of the excitation signal adopts the sinusoidal signal output. After spectrum analysis of the signal, its corresponding frequency domain waveform distribution can be obtained, as shown in Fig. 2(b). The corresponding sinusoidal signal can effectively modulate the laser pulse excitation to form the desired laser energy waveform. When the passband of the calibrated system is f_b, the rectangular pulse width τ should be selected according to the above formula. In order to ensure that the frequency band of the rectangular pulse excitation signal is sufficient to cover the frequency band of the calibrated sensor, the signal pulse width is generally 1/3 of the theoretical calculation value.

5 Experiments

5.1 Test Conditions

When measuring the time constant of the sensor, the step heat flow value is usually selected as half of the upper limit of the measured radiation amount to be calibrated. When the output spot area is fixed, adjust the laser output power to be half of the upper limit of the measurement data of the sensor. The experimental system is shown in Fig. 3.

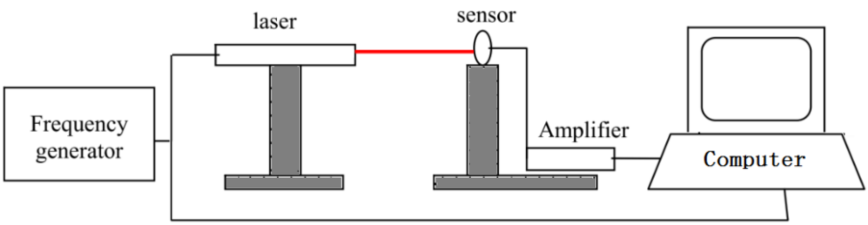
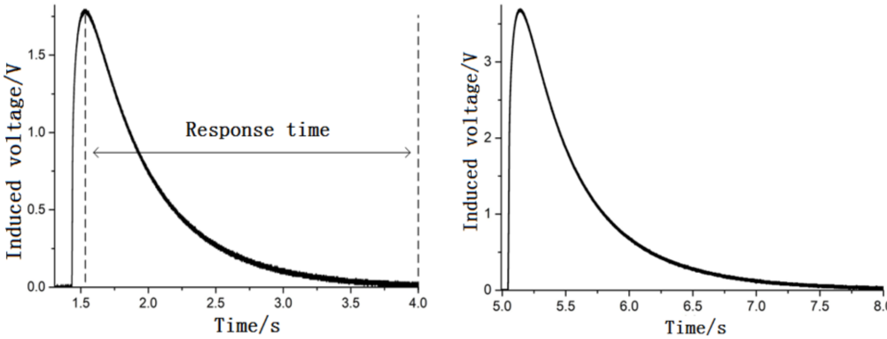


Fig 3. Laser pulse response transient quantitative identification system

5.2 Experimental Results and Analysis

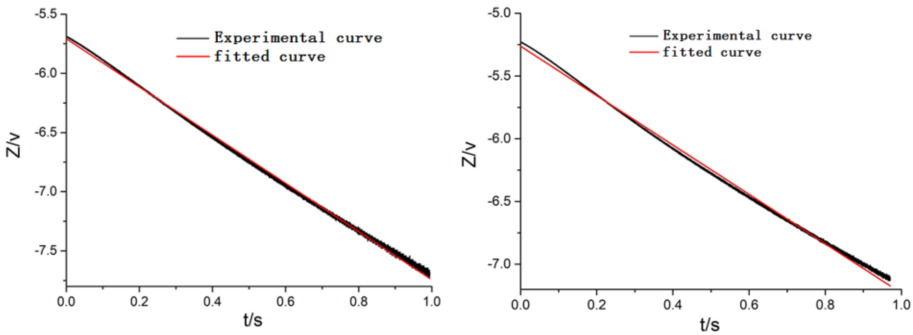
The pulse heat flow dynamic calibration system includes a signal generator to adjust the laser transistor, thereby controlling the laser to generate pulse heat flow excitation signals of different pulse widths. The dynamic calibration experiment of the sensor was completed under the condition of 10ms and 20ms pulse width, respectively. The pulse response curve of the sensor is shown in Fig. 4, and the transformation curve of the pulse response and time is shown in Fig. 5.



(a) 10ms impulse (b) 20ms impulse

Fig 4. Impulse response of signal

It can be seen from the above results that with the change of the pulse width of the laser excitation signal, the time constant of the sensor does not change significantly. The sensor time constant is 2 to 3 orders of magnitude larger than the laser pulse width, and the rectangular pulse excitation can be regarded as a signal excitation in the form of an ideal impulse function. Therefore, under near-ideal conditions, changes in pulse width have a negligible effect on the sensor time constant. In the actual pulse excitation experiment process, it is usually enough to keep the pulse width of the excitation signal less than the sensor time constant by 2 to 3 orders of magnitude, and there is no need to strictly and precisely control the pulse width.



(a) 10ms impulse (b) 20ms impulse

Fig 5. Z-t of Impulse response

There are a lot of high-frequency noises in the frequency domain of the laser pulse excitation heat flow signal and the pulse response of the heat flow sensor, which have a serious impact on the system identification results. The MATLAB low-pass filter is used to filter the original signal within a preset range. After effective data selection, resampling and high-frequency filtering data preprocessing, the change trend of the data time-frequency domain curve is clearer, and the signal-to-noise ratio is higher, which is conducive to the improvement of the accuracy of the subsequent system identification model results. It can be seen from the above results that with the change of the pulse width of the laser excitation signal, the time constant of the sensor does not change significantly. The sensor time constant is 2 to 3 orders of magnitude larger than the laser pulse width, and the rectangular pulse excitation can be regarded as a signal excitation in the form of an ideal impulse function. Therefore, under near-ideal conditions, changes in pulse width have a negligible effect on the sensor time constant. In the actual pulse excitation experiment process, it is usually enough to keep the pulse width of the excitation signal smaller than the sensor time constant by 2 to 3 orders of magnitude, and it is not necessary to strictly and precisely control the pulse width. There are a lot of high-frequency noises in the frequency domain of the laser pulse excitation heat flow signal and the heat flow sensor pulse response, which have a serious impact on the system identification results. The MATLAB low-pass filter is used to filter the original signal within a preset range. After effective data selection, resampling and high-frequency filtering data preprocessing, the change trend of the data time-frequency domain curve is clearer, and the signal-to-noise ratio is higher, which is conducive to the improvement of the accuracy of the subsequent system identification model results.

6 Conclusions

In this paper, a transient quantitative identification algorithm based on laser pulse response is designed. The feasibility of the algorithm modulation parameter control is verified by simulation analysis. Experiments show that the algorithm can respond quickly to the transient temperature change of heat flow, and has a good suppression effect on traditional noise. The system has better stability and noise suppression ability after using this algorithm for data optimization analysis.

Although this paper has completed the transient test of the pulsed laser, there are still some deficiencies. During the test, the environmental parameters have not been analyzed for the system test's success. Quantitative analysis of the impact of different environmental parameters on the test system will continue in the future.

References

[1] Liu, J., Meng, J., Liu, J., et al. (2022) “Fast reconstruction technology of a laser beam spatial transmission characteristic curve”, *Applied Optics*, 2022, 61(5), pp. 1177- 1182.

[2] Dong, Y., C., Fang, C., S., Zhu, L L, et al. “The calibration method of the circle- structured light measurement system for inner surfaces considering systematic error”, Measurement Science and Technology, 2021, 32(7):075012.

[3] Chen, G., Wang, L., Kamruzzaman M. M, et al., (2020) “Spectral classification of ecological spatial polarization SAR image based on target decomposition algorithm and machine learning”, *Neural computing & applications*, 2020, 32(10): pp. 5449-5460.

[4] Wang., J., Liu, Z., Ran, L., et al., (2020) “Feature Extraction Method for DCP HRRP-Based Radar Target Recognition via m-chi Decomposition and Sparsity- Preserving Discriminant Correlation Analysis”, *IEEE sensors journal*, 2020, 20(8): pp. 4321-4332.

[5] Wang, S., Liu, Y., Li, L., (2022) "Sparse Weighting for Pyramid Pooling-Based SAR Image Target Recognition", *Applied Sciences*, 2022, 12(7): pp. 3588-3588.
[6] Miao, S., Fan, C., Wen, G., et al., (2022) "Image denoising and enhancement strategy based on polarization detection of space targets", *Applied Optics*, 2022, 61(4): pp. 904-918
[7] Campbell D. S., Gundappa M., Diller T. E., (1989) "Design and Calibration of a Local Heat-Flux Measurement System for Unsteady Flows". *Journal of Heat Transfer*, 1989, 2(2): pp. 552-557.
[8] C. T. Kidd, (1992) "High heat-flux measurements and experimental calibrations/ characterizations", *Journal of Fluids Engineering*, 1992, 31(61): pp. 31–50.
[9] Holmberg D. G., Diller T. E., (1995) "High-Frequency Heat Flux Sensor Calibration and Modeling", *Journal of Fluids Engineering*, 1995, 117(4): pp. 659-664.
[10] Lohle. S., Battaglia J. L., Batsale J. C., et al., (2007) "Characterization of a heat flux sensor using short pulse laser calibration", *Review of entific Instruments*, 2007, 78(5): pp. 053501- 053501-6.
[11] Martucci Adolfo, De Gregorio Fabrizio, Musto Marilena, et al., (2020) "Innovative calibration methodology for gardon gauge heat flux meter", *2020 IEEE International Workshop on Metrology for AeroSpace*, 2020, 21(1): pp. 288-293.
[12] R.C. Kerschbaumer, S. Stieger, M. Gschwandl; T. Huttere, et al., (2019) "Comparison of steady-state and transient thermal conductivity testing methods using different industrial rubber compounds", *Polymer Testing*, 2019, 80(C): pp. 106121.
[13] Ma, B., Lu, M., Wang, K., et al., (2016) "Depth position recognition-related laser-induced damage test method based on initial transient damage features", Optics Express, 2016, 24(16): pp. 17698-710.