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Adaptive spectral band identification method in noncontact temperature measurement based on dynamic programming

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ABSTRACT

An adaptive method based on dynamic programming is proposed to identify the spectral band for noncontact measurement of surface temperature of heatshield materials when Fourier transform infrared (FTIR) spectrometer is used to collect the radiation spectrum in the dynamic heating environment of a high-frequency plasma wind tunnel. First, the radiation spectrum is converted to a time series. Then, high-frequency parts of the measurement spectral signal are obtained by multi-resolution analysis of one-dimensional discrete wavelet and then the suitable spectral band required by a noncontact temperature measurement is adaptively identified based on dynamic programming. Eventually, surface temperature and its corresponding emissivity can be determined. Results of the experiment conducted on a benchmark material (graphite) in the dynamic heating environment of high frequency plasma wind tunnel show the proposed method to be practical.

1. Introduction

Thermal protection materials experience an enormous heating procedure when the vehicle re-enters the Earth's atmosphere. High surface temperatures at high emissivity of non-ablation type of material are advantageous to enhance the thermal dissipation by radiation. So it's necessary to analyze the surface temperature and its emissivity to assess its heat dissipation performance in the high-frequency plasma wind-tunnel.

The thermal protection experiment in the high-frequency plasma wind-tunnel is a dynamical procedure and FTIR spectrometer is used to dynamically obtain normal spectral radiance for a series of surface temperatures and emissivities in the dynamical heating conditions. According to the energy distribution of spectral radiation, the noncontact temperature measurement method is applied to obtain the corresponding surface temperature, and then the emissivity can be derived under dynamic heating conditions [1].

Recently, most of the non-contact temperature measurement methods are based on two or multi wavelength radiation spectra [2–5]. The signals collected by single color or two color pyrometers are obtained as an integral in a narrow-band spectral radiance. The ripple of the single color signal history or between two-color signals is not considered, which means that temperature measurement procedure is robust, but a mean value. However, due to high-resolution performance of the Fourier transform infrared (FTIR), the spectrum signals are obtained. But, there are no existing integral operations in these narrow-band spectral radiances. Therefore, spectral signals have obviously small ripples, which will degrade the temperature measurement results based on two or multi-spectral wavelength method [1]. Especially accounting for different frequency characteristics with different spectral bands about the ripple under plasma background radiation in the dynamic heating environment, to the authors' knowledge, no literature is found on how to identify spectral bands for measurements to improve the fidelity of the non-contact temperature measurement method based on FTIR spectrometer, though there are reports on testing emissivity by spectrometer in the static heating environments without plasma radiation disturb and the surface temperature is measured by contact methods or pyrometer [6–11]. In addition to that, in order to avoid the plasma radiation, the external pyrometer with a defined measuring wavelength is used to obtain the radiance form the front surface of sample and it's true temperature is measured by a pyrometer based on the sample backside formed similar blackbody cavity assumption during the sample is reached to stable heating state [12].

Account obtaining multi spectral emissivities during dynamical heating procedure of plasma wind tunnel, varying surface temperature of sample should be deduced Synchronously from

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the spectral signal of FTIR spectrometer. Due to the problem that there is more or less drastic background radiation and much interference between different spectral bands, an adaptive spectral band identification method is proposed to obtain the required spectral band by combining the dynamic programming method and multi-resolution analysis of one-dimension discrete wavelet for non-contact surface temperature measurement in the dynamic heating environment of plasma wind tunnel. The proposed method is applied to process a practical experiment and the results show that the proposed method is effective and practical.

In the next section, due to existing significant plasma disturbance in the original spectral signal from thermal radiation of the front surface of heating sample, the preprocessing method of the plasma radiation spectrum is firstly described. Then, spectral radiance of test model is obtained based the preprocessed measurement signal in Section 3; adaptive spectral band identification based on dynamic programming is proposed in Section 4. Finally, experimental setup is briefly presented and experimental processing and identified results are given; besides, the emissivity of reference material, graphite, is measured from these dynamic varying surface temperature obtained based the above discussed adaptive spectral band identification results in Section 5.

2. Preprocessing the plasma radiation spectrum

The measurement of the thermal radiation characteristics of a heatshield material in a plasma wind tunnel depends on the general radiation spectrum of the test model disturbed by the spectrum of the high-temperature plasma flow. So the original spectrum should be preprocessed to subtract the plasma spectrum as far as possible by the energy superposition principle. Then

$$S_p(\lambda) = S_0(\lambda) - S_b(\lambda) \tag{1}$$

$$S'(\lambda) = S(\lambda) - S_p(\lambda) \tag{2}$$

where S_0 is the background radiation spectrum with plasma flowfield without test model; S_p is the radiation spectrum of the pure plasma without ambient background radiation. S_b is the ambient background radiation spectrum without the plasma flowfield; S is the radiation spectrum of test model with plasma radiation perturbation. S' is the radiation spectrum of test model without plasma radiation perturbation, which is finally obtained based on Eqs. (1) and (2).

3. Spectral radiance of test model obtained based on calibration of measurement system

For the content completeness of this paper, the process that normal spectral radiance of test model is obtained from measured electric signal based on calibration of FTIR spectrometer measurement system is described as following, which was present in our previous research work [1].

It is supposed that the spectral response, $K_{i,i+1}(\lambda)$ of spectrometer is constant within temperature range, $[T_i, T_{i+1}]$. Then, two spectral radiances of blackbody furnace at these known temperatures, T_i and T_{i+1}, are given respectively as

$$L_{\text{bl.}}(\lambda, T_i) = S_{\text{bl.}}(\lambda, T_i)K_{i,i+1}(\lambda) - B(\lambda), \tag{3}$$

$$L_{\text{bl.}}(\lambda, T_{i+1}) = S_{\text{bl.}}(\lambda, T_{i+1})K_{i,i+1}(\lambda) - B(\lambda). \tag{4}$$

where the spectral radiance of blackbody $L_{\text{bl.}}(\lambda, T)$ can be calculated based Planck's spectral radiance distribution formulation [13] with known temperature and emissivity of blackbody furnace; $S_{\text{bl.}}(\lambda, T)$ is the spectral measurement signal of blackbody; λ is the wavelength; $B(\lambda)$ is the ambient background radiance.

Combined with Eqs. (3) and (4), the spectral response of FTIR spectrometer measurement system can be solved by

$$K_{i,i+1}(\lambda) = \frac{L_{\text{bl.}}(\lambda, T_{i+1}) - L_{\text{bl.}}(\lambda, T_i)}{S_{\text{bl.}}(\lambda, T_{i+1}) - S_{\text{bl.}}(\lambda, T_i)}. \tag{5}$$

The background radiance is calculated from Eqs. (4) and (5), i.e.,

$$B(\lambda) = K_{i,i+1}(\lambda)S_{\text{bl.}}(\lambda, T_{i+1}) - L_{\text{bl.}}(\lambda, T_{i+1}). \tag{6}$$

Based on Eqs. (5) and (6), calibration parameters of spectral response and background radiance are determined by wavelength and static temperature points of blackbody. Then, the self-emitted normal spectral radiance $L_{\text{model}}(\lambda, T'_{\text{model}})$ from test model can be calibrated based on calibration parameters $K_{i,i+1}(\lambda)$ and $B(\lambda)$ of measurement system and radiation spectrum signal $S'(\lambda)$ of test model when $S_{\text{bl.}}(\lambda, T_i) \leqslant S'(\lambda) \leqslant S_{\text{bl.}}(\lambda, T_{i+1})$, as following.

$$L_{\text{model}}(\lambda, T'_{\text{model}}) = K_{i,i+1}(\lambda) \cdot S'(\lambda) - B(\lambda) \tag{7}$$

4. Adaptive spectral band identification based on dynamic programming

The above discussed preprocessing method is effective to remove most part of the spectrum of high-temperature plasma flow, however, some ripple still exists in different bands due to the plasma instability. This ripple is significant for noncontact temperature measurement based on FTIR spectrometer. Moreover, the plasma dynamics have different influence on the thermal radiation of test model at different time and spectral bands. Vapor and carbon dioxide have different absorbency ability at different spectral bands, which result in different disturbing frequencies and amplitude. So the steady, long and near-short wavelength spectral band without obvious ripple should be adaptively chosen to calculate surface temperatures.

Dynamic programming focuses on time-ordered decision-making problems. Therefore, by introducing time sequence, dynamic programming problems can be treated as multi-stage decision-making problems [14,15]. If a problem can be divided into some sequence stages and one decision should be made at each stage, so all of the decisions form a series, and the whole procedure is viewed as time-ordered decision-making problem. Considering the mean and mean square, the total cost function [16] is denoted as follows.

$$\begin{aligned}\left(\hat{\boldsymbol{\tau}}, \hat{\boldsymbol{\theta}}\right) &= \mathop{\arg\min}_{(\boldsymbol{\tau},\boldsymbol{\theta})\in\Gamma_K\times\Theta_K} \left\{\frac{1}{n}\sum_{k=1}^{K} W_k\right\} \\ &= \mathop{\arg\min}_{(\boldsymbol{\tau},\boldsymbol{\theta})\in\Gamma_K\times\Theta_K} \left\{\frac{1}{n}\sum_{k=1}^{K}\left(\frac{\|\mathbf{Y}_k-\mu_k\|^2}{\sigma_k^2} + n_k \log\sigma_k^2\right)\right\}\end{aligned} \tag{8}$$

Here, W_k is the cost function at the kth band, K is the number of bands, n is the number of total data points, μ_k is the mean at the kth band, σ_k^2 is the mean square at the kth band. $\boldsymbol{\theta} = (\mu_k,\ \sigma_k^2)_{k=1,\cdots,K}$; $\boldsymbol{\tau} = [\tau_1,\ \tau_2, \cdots \tau_{K-1}]$ is the $(K-1)$ partition points corresponding to the K bands. The data series $\mathbf{Y}_k = [Y_{\tau_{k-1}+1},\ Y_{\tau_{k-1}+2} \cdots Y_{\tau_k}]$ at the kth band and the coordinate is normalized, namely $\tau_0 = 0,\ \tau_K = 1$. n_k is the number of data points at the kth band, namely $n_k = \tau_k - \tau_{k-1}$. $\Gamma_K \subset \mathbf{R}^{K-1},\ \Theta_K \subset R^K \times R^K$.

In this study, the discrete calibrated spectrum radiance is treated as one set of time series sequence data. Only after the dynamic programming is applied to obtain the desired time series band, the time band should be converted into the corresponding spectral band by simple one-to-one maping relationship. And the dynamic programming method is illustrated in detail as follows.