Research on Fault Diagnosis Technology of Thermal Test Measurement and Control System Based on Data Driven

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Abstract. Temperature data, as one of the most important parameters in spacecraft vacuum thermal test, is also an important characteristic parameter for fault detection of spacecraft thermal test system. From the perspective of numerical heat transfer, the physical and mathematical models of thermal test specimens are established by using finite difference method. Based on the data driving of specimen measurement temperature and heating power, the mathematical model coefficients are fitted by the combination of least squares and sliding window filtering, and then realize the on-line prediction of temperature data and fault detection of thermal test measurement and control system. Based on the thermal test data of the solar wing of a certain type of spacecraft, the above-mentioned method was verified by physical experiments. The experimental result shows that the method can accurately and effectively realize the temperature prediction not less than 2 periods, and the prediction accuracy is less than ±2℃. It can provide an effective fault detection means for the thermal test measurement and control system.

1. Introduction
The vacuum thermal test is the most expensive and most complex test project in the development process of spacecraft. It plays an important role in the analysis of mathematical model of spacecraft thermal design and the verification of thermal control system, as well as the verification of various functions and performances of spacecraft and its components under high and low temperature. Temperature data is one of the most important parameters in spacecraft thermal test. It is the main parameter of the core control and its effect of the thermal test measurement and control subsystem. The function well of spacecraft thermal test measurement and control system is an important guarantee to ensure the testing safety. At present, the fault diagnosis and analysis of measurement and control system state are mainly carried out by manual observation of the software operation state and manual analysis of the trend of temperature change combined with historical experience. These methods are less automated and less reliable. Through research, we can see that the contrastive analysis of predicted temperature and actual temperature can realize the fault diagnosis of spacecraft thermal test measurement and control system effectively.

In view of the variety and complex thermal characteristics of specimens and its components, the logical of input and output nodes for temperature measurement and control are complex. At present, the main methods of temperature prediction are linear interpolation method, maximum likelihood method and neural network method[1-2]. Among them, due to the temperature data characteristic of thermal test is non-linear, the error of linear interpolation method is large. In addition, although the average error of temperature prediction for spacecraft thermal test by using neural network method is small, but the training samples must cover the prediction range completely which limits its usage...
scenarios. At the same time, when the number of temperature points is large, the number of neural network model nodes is also large which affects the algorithm operation speed. It can’t realize the online correction of the neural network model.

In order to realize the fault diagnosis of measurement and control system in spacecraft thermal test, a data-driven temperature prediction algorithm is proposed in this paper. Based on the physical model of spacecraft thermal test, the method combines the least squares method with sliding window filter, and combines the on-line temperature and heating power data. The on-line identification of the parameters of the thermal mathematical model and accuracy prediction of the temperature are realized. The error of the temperature prediction is less than ±2℃, which can effectively meet the temperature threshold requirement of the fault diagnosis of thermal test measurement and control system.

2. Establishment of physical model for thermal test

In the process of establishing and analyzing the mathematical and physical model of spacecraft thermal design, the finite difference method can be used to model the internal points of components[3-4]. By using this method, the accessory components such as cables and connectors in spacecraft can be neglected, and the key components in spacecraft can be simplified to basic geometric models such as cylinders and cubes. The radiation, heat conduction and convective heat values of the key components can be calculated by software design.

Firstly, the non-heat source specimens are taken as the research object, and each temperature measuring point and its accessory area on the specimens are identified as a temperature measuring unit. When the specimen is not affected by external heat source, the change of internal energy of each temperature measuring unit is mainly affected by external heat radiation and heat conduction of other temperature measuring units. The thermophysical model of each temperature measuring unit is shown in (1).

\[ M_i \frac{dT_i}{dt} = -S \alpha \sigma (T_i^4 - T_{ss}^4) + \left( T_{i1} - T_i \right) \frac{\Delta S_{i1}}{I_1} + \left( T_{i2} - T_i \right) \frac{\Delta S_{i2}}{I_2} + \cdots + \left( T_{im} - T_i \right) \frac{\Delta S_{im}}{I_m} \] (1)

in (1), \( M \) is the mass(kg) of temperature measuring unit, \( c \) is the average specific heat capacity(J/kg.K) of temperature measuring unit, \( T_i \) is the temperature(K) of the No \( i \) temperature measuring unit, \( T_{ss} \) is the heat sink temperature(K), \( S \) is the external radiation area (m²), \( \alpha \) is the emissivity of the specimen, \( \sigma \) is the blackbody radiation constant of specimen, \( T_1 \), \( T_2 \), \( \ldots \), \( T_m \) is the temperature(K) of the remaining temperature measuring units on the specimen, \( \lambda \), \( s \) and \( l \) is the thermal conductivity coefficient (W/m.K), thermal conductivity area (m²) and thermal conductivity distance(m) between the other units and the current units respectively, \( m \) is the number of specimen temperature measuring units.

The formula (2) can be obtained by the data discretization of (1),

\[ \frac{T_{i(k+1)} - T_{ik}}{\Delta t} = -S \alpha \sigma (T_{ik}^4 - T_{ss}^4) + \left( T_{i1} - T_{ik} \right) \frac{\Delta S_{i1}}{I_1} + \left( T_{i2} - T_{ik} \right) \frac{\Delta S_{i2}}{I_2} + \cdots + \left( T_{im} - T_{ik} \right) \frac{\Delta S_{im}}{I_m} \] (2)

in (2), \( \Delta t \) is the time step, \( k \) time is the current time, the next time is the \( k+1 \) time.

When the external heat source which affects the specimen is considered, the heating elements of the heat source include infrared lamp, infrared cage and heating sheet. When establishing the thermal physical model, the infrared lamp or heater can be equivalent to a corresponding number of heating units according to the number of infrared lamp or heater, and the infrared cage can be equivalent to a corresponding number of heating units according to the number of delimited thermal zones. Therefore, when considering the influence of external heat sources, the individual temperature measuring unit of the specimen is affected not only by external heat radiation and heat conduction of other temperature measuring units, but also by external heat radiation or heat conduction of the heating unit. The thermal physical model discretization formula of the temperature measuring unit is shown in (3).

\[ \frac{T_{i(k+1)} - T_{ik}}{\Delta t} = -S \alpha \sigma (T_{ik}^4 - T_{ss}^4) + \left( T_{i1} - T_{ik} \right) \frac{\Delta S_{i1}}{I_1} + \left( T_{i2} - T_{ik} \right) \frac{\Delta S_{i2}}{I_2} + \cdots + \left( T_{im} - T_{ik} \right) \frac{\Delta S_{im}}{I_m} + \sum_{i=1}^{\eta} \alpha_i P_{ik} \] (3)
In (3), $P_S$ is the power (W) of the No.s heating unit, and $\alpha_s$ is the power influence factor of the No.s heating unit on the power of the second heating unit. The physical meaning of $\alpha_s$ is that the heat absorption rate of the temperature measuring unit to the heating unit, the $\alpha_s$ is a constant and the $n$ is the number of heating elements.

3. Fault diagnosis based on temperature prediction model algorithms

Based on the establishment of the specimen thermophysical model, the mathematical model based on (3) is established to realize the temperature prediction model algorithms, which realizes the fault diagnosis of measurement and control system further[5].

During the specimen thermal test, the product quality $M$, average specific heat capacity $c$, emissivity $\alpha$, blackbody radiation constant $\sigma$, heat sink temperature $T_e$, thermal conductivity coefficient $\lambda$, thermal conductivity area $s$, thermal conductivity distance $l$ and unit power influence factor $\alpha_s$ are approximately constant, so they can be approximated as constant. Therefore, (3) can be simplified as (4).

$$T_{i,k+1} - T_i = C + A_0 T_i + \sum_{j=1}^{m} A_j (T_{j,k} - T_i) + \sum_{s=1}^{n} A_{m+s} P_{s,k}$$

(4)

In (4), $C$ and $A_{0-A_{m+n}}$ are constants, and the (4) can be further simplified to (5).

$$T_{i,k+1} = C + A_0 T_i + \sum_{j=1}^{m} A_j T_{j,k} + \sum_{s=1}^{n} A_{m+s} P_{s,k}$$

(5)

In (5), $T_{i,k}$ are the temperature values of the No.i temperature measuring unit at No.k time, while $C$ and $A_{0-A_{m+n}}$ are the unknown constant parameters. According to the principle of least squares fitting algorithm, when the temperature values of $T_{k+1} \sim T_{k+1}$ are known, while $\epsilon \leq m+n+1$ the fitting of coefficients such as $C$ and $A_{0-A_{m+n}}$ can be realized. Then, when the real values of $T_{k+1}$ is known, the prediction of the No.i temperature measuring unit temperature values at the time of $k+2$ can be realized.

Because of the nonlinearity of temperature is relatively strong, then, the variation of $C$ and $A_{0-A_{m+n}}$ coefficients will affect the stability of temperature prediction in the process of thermal test. A sliding filter algorithm is adopted here. The length $p$ of sliding window is set to not less than $m+n+1$. Before the temperature of the $k+2$ time is predicted during the thermal test, the coefficients $C$ and $A_{0-A_{m+n}}$ can be identified and updated on-line base on the driving data[6], which include all of the temperature measuring unit temperature values from the $k-p+1$ time to the $k+1$ time. The algorithm model is shown in (6).

$$
\begin{bmatrix}
T_{ik} & T_{ik} & \ldots & T_{ik} & P_{ik} & \ldots & P_{ik} \\
1 & 1 & \ldots & 1 & 1 & \ldots & 1 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
1 & 1 & \ldots & 1 & 1 & \ldots & 1 \\
\end{bmatrix}
\begin{bmatrix}
C \\
A_0 \\
A_1 \\
A_m \\
A_{m+n} \\
\end{bmatrix}
= 
\begin{bmatrix}
T_{ik+1} \\
T_{ik+2} \\
\vdots \\
T_{ik+p} \\
\end{bmatrix}
$$

(6)

This method can eliminate the error of temperature prediction caused by the deviation of coefficient value, improve the precision of temperature prediction value in the temperature measurement unit of the specimen, and realize the fault diagnosis of the thermal test measurement and control system.

4. Test verification and result analysis

In order to verify the algorithm of temperature prediction model, this paper takes the thermal vacuum test of a certain type spacecraft solar panel as the research object, uses the MATLAB tool to implement the temperature prediction algorithm, and analyses the results and performance of the algorithm based on the experimental data.

The mathematic model of the solar panel is established base on its test physical model. A total of 15 temperature measuring sensors were implemented on the positive surface of the solar panel. The infrared lamp array, which acts as the heat source, contains 156 infrared lamps. The control period of
measurement and control system is 6 seconds[7-8]. Based on the above parameters, the coefficient of temperature prediction algorithm is established, which include $m$ is 15, $n$ is 156 and the length of sliding window $p$ is 173. This thermal test conditions include four cycles of high and low temperature. The infrared lamp array based on closed-loop temperature control algorithm is used to realize high temperature conditions. The high temperature control range is 80±2℃. The power supply of lamp array is cut off infrared in the low temperature conditions. In the high temperature conditions, because of its large number and high power of power supply, the fault probability of test measurement and control system is high. In this paper, the data of second cycle rising and holding stages are selected as model validation data. The data include temperature of measuring point, current and voltage of infrared lamp.

The temperature prediction results of the No.1 and No.5 temperature measuring points are analyzed. The actual temperature values and the pre-1 period predicted temperature values are shown in Figure 1 and Figure 2, respectively. The temperature prediction errors are shown in Figure 3.

![Figure 1](image1.png)  ![Figure 2](image2.png)  ![Figure 3](image3.png)

Figure 1. The contrast curve between the actual temperature of solar wing No.1 measuring point and the pre-1 period predicted temperature.  
Figure 2. The contrast curve between the actual temperature of solar wing No.5 measuring point and the pre-1 period predicted temperature.  
Figure 3: The errors of pre-1 period predicted temperature of solar wing No.1 and No.5 measuring points.

We can see in the Figure 1 and figure 2 that the pre-1 period predicted temperature curve was basically consistent with the actual temperature curve in the process of rising and high holding temperature in the second cycle. From Figure 3, it can be seen that the error of pre-1 period predicting temperature is basically less than ±1℃.

If take the pre-1 period predicted temperature value of No.1 and No.5 measuring points as the current actual value, the pre-2 period predicted temperature can realize through the temperature prediction model algorithms. The error between the pre-2 period predicted temperature and the current
actual value is shown in Figure 4. Similarly, the error between the pre-3 period predicted temperature and the current actual value is shown in Figure 5.

From Figure 4 and Figure 5, it can be seen that the per-2 period temperature prediction errors of No. 1 and No. 5 measuring points are basically less than ±2℃, and that of the error of pre-3 period are basically less than ±3℃.

Figure 6 is the maximum error curve of the predicted temperature of all 15 measuring points of the solar wing, which include the pre-1, pre-2 and pre-3 period. From Figure 6, it can be seen that the maximum error of the pre-1, pre-2 and pre-3 period predicted temperature of all 15 measuring points are less than ±1℃, ±2℃ and ±3.5℃ respectively. In the actual thermal test, the temperature control threshold of working condition is generally ±2℃, beyond which is the failure of thermal test. Therefore, in order to realize the accurate prediction temperature, remove the influence of fault power and temperature data, the model of pre-2 period predicted temperature data was selected as the fault diagnosis judgment data. When the error between the pre-2 period predicted temperature value and the actual temperature value is larger than 2℃, the fault of the test measurement and control system can be diagnosed, which prompts the tester to carry out systematic inspection.

In order to further verify the effectiveness of this algorithm in fault detection of measurement and control system, the fault points can be set by selecting any period in the process of fault detection, and analysis the detection results of the fault points. In this verification, the 198th detection period was selected. The failure point mode was set to the output faults of No. 109 infrared lamp and No. 110 infrared lamp, which corresponds to No. 2 measurement point. The temperature change value of No. 2 was set according to the historical fault law. Then the temperature data after the fault was predicted by
the fault detection algorithm described in this paper. The temperature prediction results were shown in the Figure 7.

We can see in the Figure 7 that the temperature prediction values were not affected by the system fault at the 198th detection period. The deviation between the actual temperature and the predicted temperature was -24.1 ℃, which was larger than the fault judgment threshold which is ±2℃, and the fault detection of the measurement and control system was realized accurately.

Acknowledgements
From the point of view of numerical heat transfer, the thermal physical model of spacecraft thermal test specimens was studied in this paper. The thermal mathematical model is established by finite difference method. Based on the historical temperature data and heating power data of the measurement and control system, the parameters of thermal mathematical model can be fitted on-line by the combination of least square method and sliding filter algorithm. In addition, the on-line temperature prediction and fault diagnosis are reached. The above method is validated by physical experiments using real spacecraft solar wing thermal test data. The Verification results show that when the prediction period is selected as pre-2 periods, the temperature prediction error can be guaranteed within 2℃ and meet the temperature control threshold of thermal test, and the fault diagnosis of thermal test measurement and control system can be effectively realized.

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