Optimal Sensor Placement of Health Management for Thermal Protection System on RLV

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Abstract: When a Reusable Launch Vehicle (RLV) travels through the atmosphere there should be strong aero heating around it, so a Thermal Protection System (TPS) would be used to protect the vehicle structures from aero thermal ablation. However, the TPS structure may fail more frequently than normal vehicle structures because of the severe environment and load conditions, while a TPS failure can even lead to a catastrophic breakdown of vehicle structures. To keep the RLV safe, the TPS must be monitored real-time. To learn the heat transfer inside a ceramic TPS tile finite element models are built, and computation made with them indicates that temperature monitoring and frequency monitoring of the TPS structure should be effectual for fault detection. Health management for TPS is one of the key technologies for space vehicle. The paper puts forward a method that analyze and valuation the system states by monitoring the key function index sign of TPS. The concept of health management for Thermal Protection System of space shuttle and the principles of health monitoring are introduced. The principles of sensor selection and layout optimization method for TPS Health Management are discussed.

1. INTRODUCTION

In addition to aerodynamic thermal load primarily undertaken by thermal protection system (TPS) of a reusable launch vehicle (RLV) during flight, it must bear various non-heating loads including alternative temperature between -150°C and +55°C, aerodynamic noise and deceleration overload, etc.[1]. It is much likely for Insulation tiles that have been struck by thermal insulation materials splitting away off an external tank or space debris to break or fall off. If the number of Insulation tiles falling off has reached the limit, RLV may be broken into pieces due to giant pressure and super high temperature at the time of atmospheric re-entry, which further gives rise severe accidents.

Over the past several decades, heat transfer of the thermal protection structure has been theoretically analyzed and experimentally investigated by multiple scholars. Cunning ton et al. made surveys about effective thermal conductivity of 7 kinds of multilayer insulation structures in 1967 together with analyzing heat transfer in theory; in addition, they also took advantage of an approximation method for radiant heat absorption analysis [2]. According to Keller et al., the approximation method described above and the modified diffusion approximation method are both utilized to analyze radiation heat transfer proposing an internal heat conduction analysis model for different multilayer insulation structures [3]. The two-flux theory is adopted by Kamran et al. who has
discussed about optimal multilayer structure design to analyze radiative transfer on one hand; on the other hand, the finite-difference numerical analysis method is further used to obtain the corresponding solution and the finite volume method to analyze energy conservation control equation \([4,5]\). Moreover, countries of great power in aerospace such as America have been also dedicated to improving aerodynamic heating prediction accuracy based on computational fluid mechanics, perfecting transient response analysis approaches for TPS temperature field and combining such two analysis processes together to enhance mass estimation precision of TPS \([6,7,8]\). Among them, some investigations on health management of the structure have been involved with TPS or taken it into account \([9,10]\). Regarding health monitoring technique test targeted at nose cone TPS performed by overseas scholars who resort to X-38, X-38 is a Lifting body re-entry vehicle designed as emergency return spacecraft for International Space Station crew developed by NASA, they lay emphasis on studying several sensor technologies available for TPS health monitoring, including acoustic emission, micrometer and infrared imaging\([11]\). As for researches on thermal protection structure surface damages and strain isolation layer degumming faults, rapid non-destructive evaluations on these failures in the process of ground maintenance were stressed \([12,13,14]\).

Experts in ground adopt electric equipment-based monitoring to comprehend conditions of Insulation tiles in a better manner and further carry out fault analysis and judgment. However, photos and images that are not clear enough give rise to information incompleteness and non-determinacy. Consequently, it becomes less likely to estimate causes to such faults and the overall health condition of a space shuttle. Moreover, neither instantaneity of fault processing nor high accuracy and reliability of fault diagnosis is achieved as fault analysis consumes a long time, which also signifies that safety of RLV return process cannot be exactly assessed in advance.

Therefore, greater importance should be attached to studies on health management of RLV TPS for the purpose of effectively preventing catastrophic failures incurred by phenomena described above. We have studied the composition, failure mode and influence analysis of Thermal Protection System on RLV, on the basis of which, this paper mainly the selection of sensors and the optimal layout method.

2. SELECTION OF TPS HEALTH MONITORING SENSOR

Referring to the experience of the US NASA in X-33 and X-38 using Fiber Bragg Grating (FBG) high temperature sensor temperature sensor for health monitoring, TPS health management has the following three requirements for sensors.

1) The sensor (with its signal transmission line) must be adaptable to high-low temperature environment where it is located at and guaranteed to be in a position to run reliably and stably in limiting temperature.

2) Q-percentile life of the sensor (with its signal transmission line) must be longer than that of thermal protection materials in the same position; otherwise, monitoring system maintenance cannot make up for thermal protection structure disassembly.

3) The sensor must be sufficiently consistent and reliable.

By taking accuracy, cost and quality, etc. into consideration, Fiber Bragg Grating (FBG) high temperature sensor was selected in this paper. The corresponding installation mode was designed to be internally embedded.

Generally speaking, the FBG Intelligent Health Monitoring system mainly consists of the following three parts: FBG sensor system, signal transmission and collection system, data processing and monitoring system. Among them, FBG sensor system, including the choice of FBG sensors, FBG sensor network in the structure of the layout scheme, select specific modulation and performance requirements of FBG sensor, and consider the topology of FBG sensor. The signal transmission and acquisition system include the calibration of FBG sensors, the sampling module and the storage structure and mode of the massive real-time data. Data processing and monitoring system is the core of health monitoring system, including the analysis of the validity of a large number of data, the
3. OPTIMAL SENSOR PLACEMENT OF TPS

Optimal sensor network design was conducted for TPS by focusing on sensor placement and employing temperature as the principal monitoring object.

Fiber optic sensor (FOS) was selected as the research object of this study to perform sensor placement optimization. As assumed, the mass of a single sensor was denoted to be \( m \) and the corresponding detection probability to be \( g \); in zones of high, medium and low temperature, sensors with a number of \( x, y, z \in N \) were respectively placed to constitute an extensive health monitoring sensor network. The goal of such optimization is to achieve a detection rate up to the standard by virtue of the least quantity of sensors. As long as the type of sensor has been determined, total mass of the entire sensor network can be deemed as a function of the sensor quantity, that is, \( M = M(n_1, n_2, n_3) \); besides, TPS fault detection rate \( P \) acquired by the whole sensor network is a function of both the sensor quantity and the position matrix \( J \) of sensor placement. To be specific, \( J \) is constituted by a coordinate vector \((x, y, z)\) of each sensor placement point and \( P = P(n_1, n_2, n_3, J) \). Therefore, sensor network placement optimization should be conducted on the premise of maximizing \( P \), but minimizing \( M \). In the case that it is aimed at \( M \) minimization, the relevant constraint condition can be described as fault detection probability no less than the required value; by contrast, if the objective of it is to maximize fault detection probability \( f(M) \), such a condition turns into the total mass of this sensor network no more than the specified value.

Provided that the system detection rate is not below 90\%, the number of sensors can be equal to a variety of values. Nevertheless, RLV has a very strict requirement for system mass control. Considering this, the sensor quantity should be proper, not too much. As a result, a scheme utilizing the minimized quantity (i.e., mass minimization) should be selected from various solutions up to relevant requirement for placement. In this condition, the mathematical model of such an optimization problem is simplified as follows,

\[
\text{Min } (M(n_1, n_2, n_3)) \\
\text{s.t. } P \geq 0.9, x, y, z \in [u, v, w] \text{ and } n_1, n_2, n_3 \in N
\]

where \( P \geq 0.9 \) is referred to as inequality constraint acting as a constraint condition of this optimization model, signifying TPS fault detection probability achieved by the sensor network; \( n_1, n_2, n_3 \) are optimization or decision variables respectively, that is the number of sensors; \([u, v, w]\) is space \( R^n \) subjected to a non-void condition, if solved in a set \( D \) and \( D = \{ (n_1, n_2, n_3) | n_1, n_2, n_3 \in N \} \), \( D \) stands for the feasible region of this optimization problem. After the optimal number of sensors (i.e., optimal sensor network mass) has been achieved by solving this problem, system detection rate in the corresponding condition can be figured out.

Mass distribution of the entire TPS should be under control. Besides, the proper sensor quantity and placement position be defined, so as to gain a maximum TPS fault detection rate. Contrary to the optimization model described above, such a model is expressed as follows,

\[
\text{Min } (-P(n_1, n_2, n_3, J)) \\
\text{s.t. } M \leq M_{\text{max}}, x, y, z \in [u, v, w] \text{ and } n_1, n_2, n_3 \in N
\]

where \( M_{\text{max}} \) is the upper limit of sensor network mass, considered to be the constraint condition of this optimization model. Likewise, it is solved in a set \( D \), \( D = \{ (n_1, n_2, n_3) | n_1, n_2, n_3 \in N \} \) and \( D \) serves as the feasible region of the related optimization problem. In order to obtain the optimal system detection rate, this problem should be resolved to further figure out the number of sensors and their
placement positions (i.e., the optimal sensor network mass distribution) under the corresponding circumstance.

Optimal RLV sensor network placement design is a multidisciplinary and multi-objective optimization problem involving subject knowledge of flight vehicle design, sensor selection, test system design and fault detection, etc. As for sensor placement of TPS, it is a broad problem of massive sensors and should be oriented by local optimization and minimum fault isolation in line with real needs. We discuss the detection rate based optimal sensor placement for thermal protection structure.

When the finite element mode has been established for the thermal protection structure together with the determination of corresponding parameters, each node of this model represents one possible sensor placement position, the measured value (or statistical or sensitive information of distortion) of which can be obtained through finite element analysis. As for sensitive data of other parameters, such as model form and stiffness degradation, it is probable for us to acquire them by virtue of the FEM model that takes material performance reduction into account.

Sensor placement is meant to find a set of sensor placement positions to guarantee that sensors distributed on the thermal protection structure are able to accurately identify state of the structure on the premise of satisfying identification probability required by analysis and evaluation. In general cases, the approach to optimal sensor placement is described as follows. “n position(s) to be selected and a sensor(s) to be utilized are given on the premise of $a = n$ to ensure the highest detection capability.”

Optimal sensor placement realized by Snob fit is an optimization scheme applicable to boundary restrictions of the target function subjected to interference. Major advantages of adopting such optimization software lie in the fact that only the following optimization problem needs considering without determining positions of sensors to be selected in advance.

$$\min f(x)$$
$$s.t. x \in [u, v]$$

(3)

where $x$ is continuous and $[u, v]$ constrained in non-void space $R^n$.

The above equation of optimization problem plays a role in defining the position of one sensor. $x$ refers to coordinate of a sensor placed to recognize configuration state at the maximum probability when the thermal protection structure has been sound or damaged. $Px$ denoting correct configuration state recognition probability is acquired to realize application of optimization function in Equation (3) applied, in which case, $f(x) = -Px$ and restricted space $[u, v]$ of $x$ depends on physical dimension of the structure. So optimal sensor placement can be determined by solving this equation.

Simulation analysis on local thermal protection structures is implemented by Ansys. Principle of transient analysis is to motivate the structure by a sinusoidal alternating dynamic load, so that its vibration frequency changes to 600Hz in 0.2s. As auxiliary input of an active detection algorithm, such a excitation is a normal random variable with a mean value of 0.254mm and a variable coefficient of 0.5. Considering that the excitation only acts on one position, the piezoelectric actuator, there is no need to regard this parameter as a random process or field. Finite element analysis was repeatedly loaded for the model to provide sample sources for further statistical analysis. Sound operating state and damaged operating state were respectively simulated with 30 excitations each, which could be realized by identical random excitation amplitude, so as to set up mean eigenvector and feature covariance matrix required by damage recognition and detection algorithm. After that, 30 random excitations were utilized to simulate 30 sound and 30 damaged operating states separately to estimate advantages and disadvantages of sensor placement.
Figure 1. Typical Sensor Placement of Insulation Tile

Figure 1 presents the typical sensor placement. That located at sensor 1 is a fixed loading excitation point, while those at sensors 2, 3 and 4 are measuring points whose positions keep changing. To connect the insulation tile and the fuselage, 15 bolts were put into use; under this circumstance, bolt looseness and damage are incurred at point 11.

A series of features were extracted from time displacement data of analog input and they corresponded to signals of given parameters. Features that have been selected in this paper consisted of time and frequency domains. In detail, the former is generated by response autocorrelation and cross correlation of 3 different sensors. Time data of such 3 sensors were adopted to gain three functions of autocorrelation and three functions of cross correlation, where all these functions have definite shapes; meanwhile, the first two order responses of correlation functions could be also achieved by 4th central moment. As a result, 18 features in time domain were produced. Likewise, autocorrelation and cross correlation functions of the sensors’ frequency domains were obtained dependent on frequency domain features; with the first order response of the correlation function acquired by 4th central moment as well, 12 frequency domain features are gained. In total, there is a 30-dimension eigenvector used for state classification. Furthermore, a state classifier was acquired by Bayes’ decision theory and detection rate maximization. Classification of each variety of configuration states should be based on mahalanobis distance shown in equation (4).

\[ d_j(x) = (x - \mu_j) \sum_j^{-1} (x - \mu_j) \]  

where \( j \) serves as an index of configuration state, \( x \) as eigenvector for classification, \( \mu_j \) and \( \sum_j \) respectively as mean vector and feature covariance matrixes for “learning” data of the given configuration state. The feature covariance matrix must be nonsingular, because inverse matrix of \( \sum_j \) is demanded by the mahalanobis distance. To ensure it, some features should be removed from such series. Finally, relevant states were classified by a 12-dimension eigenvector. Based on outcomes of the first round of sound and damaged operating state simulation with 30 excitations, output feature vector recognition and classification foundations were established for sound and damaged states.

Then, evaluations based on classification equation for sound and damaged operating state simulation with 30 excitations each were performed to continue state classification. Additionally, relevant states were judged by the minimum value. A set of sensor placement generated a configuration state detection classification matrix correspondingly.
According to this classification matrix, both fault detection rate and false alarm rate of a corresponding sensor array can be figured out, which should be repeated targeted at different kinds of sensor placement to realize optimal sensor placement by Snobfit as an optimization toolkit of MATLAB. Figure 2 is a schematic diagram of sensor placement after the optimization. In this case, positions of four sensors are in the middle of 4 and 5, 5 and 6, 10 and 11, and 11 and 12 respectively. Through calculations, fault detection rate turned out to be 97.8% and the false alarm rate to be 3.0%.

4. SUMMARY
(1) According to the special requirements of RLV heat-resisting system, the fiber Bragg grating high temperature sensor is selected as the temperature measurement sensor.
(2) The optimum design criterion for the sensor layout of the heat-resistant system is minimization criterion of identification error, model reduction criterion and interpolation fitting criterion.
(3) The sensor arrangement of the heat-shield system is based on the actual requirements of local optimization and minimum fault isolation as the main guiding ideology. In this paper, detection rate based optimal sensor placement for thermal protection structure is studied.

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