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Dynamic Analysis of an Aeroengine Temperature Detector System based on a Lumped Parameter Model

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Abstract: ***Addressing the issue of dynamic response amplification in the aeroengine temperature detector system under high-temperature and vibrational environments, a 12-degree-of-freedom lumped parameter dynamic model consisting of the detector body, connecting tube, thermosensitive component, and bracket was established to analyze the inherent characteristics and vibration response of the system. The results indicate that the low-order modes of the system primarily manifest as overall torsional, translational, and locally coupled vibrations. The thermosensitive component exhibits significant responses in both lateral and rotational directions, with the main risk frequency bands of the system concentrated around 400~500 Hz and 844 Hz. Further analysis reveals that the dynamic stress at the root weld of the thermosensitive component is relatively high, making it a potential weak spot in the system. The research findings can provide a reference for the dynamic analysis and reliability design of aeroengine temperature detector systems.***

Keywords: Aviation engine temperature detector system, Lumped parameter model, Inherent characteristics, Dynamic response, Thermosensitive components**.**

1. Introduction

Aircraft engines operate in complex environments with high temperatures, high rotational speeds, and wide-frequency random vibrations. Temperature detectors installed in the engine compartment or adjacent to load-bearing structures not only perform temperature sensing and signal transmission, but also bear vibration transmitted by the engine, mounting base, and local connections. For elongated assembly structures composed of thermo-sensitive components, connecting tubes, pressure conversion components, and brackets, uneven mass distribution, connection stiffness differences, and local flexibility may amplify vibration responses and affect measurement stability and joint safety.

Existing research has yielded many achievements in aeroengine temperature testing, pipeline system vibration, and flexible multibody dynamics modeling. However, direct dynamic research on aeroengine temperature detector systems remains relatively limited, especially in system-level modeling of the coupling among the detector body, connecting tube, thermo-sensitive component, and bracket, and in identifying local weak regions.

Based on this, this paper establishes a system-level dynamic model for an aeroengine temperature detector system using the lumped parameter method. Natural frequencies, vibration modes, time-domain and frequency-domain responses, and root-weld dynamic stress are analyzed to identify key response parts and potential weak areas, providing references for structural design, connection parameter selection, and reliability evaluation.

2. Lumped Parameter Model

The research object primarily consists of the temperature detector body, connecting tube, thermo-sensitive component, and bracket. The thermo-sensitive component is located in the measured thermal environment and serves as the key sensing component; the connecting tube transfers load and vibration; and the bracket fixes the system to the engine mounting foundation. Welded joints, clamps, quick clamps, and riveted connections form the main constraints of the system.

Figure 1: Typical aeroengine temperature detector sensor

To balance model expressiveness and computational efficiency, the four main components are regarded as rigid bodies moving in a plane, with each component having three degrees of freedom: x-direction displacement, y-direction displacement, and rotation angle around a direction perpendicular to the plane of motion. The generalized coordinates of the system can be written as follows:

$$q = [x_1, y_1, \theta_1, x_2, y_2, \theta_2, x_3, y_3, \theta_3, x_4, y_4, \theta_4]^T$$

In the formula,$x_i$and$y_i$represent the displacement components of the centroid of component M_i in the global coordinate system, respectively ; θ_i epresents the rotation angle of component M_i around the axis perpendicular to the motion plane.

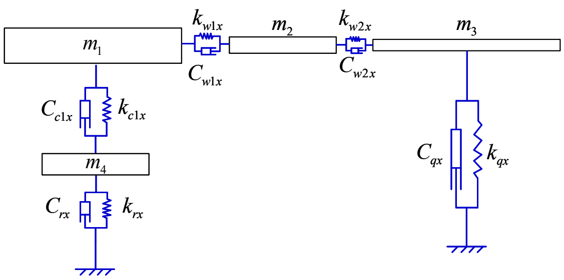

Figure 2: Dynamic model of temperature detector system

Under the assumption of small vibrations, the differential equation of motion for the system can be expressed as:

$$M\ddot{q} + C\dot{q} + Kq = F(t)$$

In the formula, M, C, and K represent the system mass matrix, damping matrix, and stiffness matrix, respectively, while F(t) denotes the external excitation vector. The mass and rotational inertia parameters are read from the three- dimensional model; the equivalent stiffness of welds, quick clamps, clamps, and riveted connections is calculated based on material mechanics relationships; and the damping parameters are determined using connection-level equivalent viscous damping. This model can reflect component coupling and provides a basis for inherent characteristics and dynamic response analysis.

Considering the elongated structure of the thermo-sensitive component, it is difficult to describe local bending and root-weld stress directly using a system-level rigid-body model. Therefore, the thermo-sensitive component is further simplified as a Bernoulli-Euler beam, and a local flexible-body model is established. This local model is used to extract bending deformation and alternating bending stress at the weld section, forming a global-local analysis framework with the system-level model.

3. Inherent Characteristic Analysis

After ignoring damping and external excitation, the free vibration equation of the system can be written as:

$$M\ddot{q} + Kq = \mathbf{0}$$

The corresponding characteristic equation is:

$$(K - \omega^2 M)\varphi = 0$$

In the formula, ω epresents the natural frequency, and φ represents the mode shape vector.

Table 1: Natural frequencies and main vibration modes of the system

order	Natural frequency/Hz	The main vibration modes
1	58.0	Overall system turnaround
2	457.1	Horizontal translation of the stent
3	1718.2	Overall translation of the system
4	1965.3	Connecting tube - local torsion of thermosensitive components
5	2529.1	Overall translation of the system
6	7507.6	Local vibration of thermosensitive components

As can be seen from Table 1, the first-order natural frequency of the system is 58.0 Hz, corresponding to the overall torsional dominant vibration, indicating that the system exhibits a pronounced characteristic of overall coordinated motion in the low-frequency range. The second-order mode shape primarily manifests as y-directional translation of the support, while the third and fifth orders are related to the overall translation of the system, reflecting the significant influence of installation supports and the mass distribution of main components on low-order modes. Local vibrations such as those of connecting pipes, thermosensitive components, and supports gradually emerge after the fourth order, indicating that the stiffness and connection constraints of local components affect mid-to-high-frequency responses.

From the perspective of mode shapes, the system's vibration modes can be categorized into four types: overall torsion and translation, local component translation, local component torsion, and coupled vibration of connecting pipes and thermosensitive components. The overall modes primarily determine the low-frequency response level, while the local modes are related to the local stiffness of thermosensitive components, connecting pipes, and supports. Due to the small mass, slender structure, and complex end constraints of the thermosensitive components, their local vibrations are more prone to amplification under external random excitation, making them the focus of subsequent dynamic response analysis.

4. Parameter Impact Analysis

Based on the analysis of inherent characteristics, further investigation was conducted into the impact of connection stiffness and component rotational inertia on the system's dynamic characteristics. Since the temperature detector system consists of multiple connection structures connected in series, changes in stiffness at different connection points alter the vibration energy transfer path. The analysis indicates that quick-clamp connections, clamp connections, and rivet connections have a significant impact on low-order natural frequencies. When the stiffness of key connections is low, the system's local constraint ability decreases, making thermal components and connecting tubes more prone to response amplification.

In terms of quality parameters, the rotational inertia of heat-sensitive components, connecting tubes, and brackets exhibits high sensitivity to local modes. For slender, low-mass components, changes in rotational inertia not only affect their own rotational modes but may also alter the coupling relationship with adjacent components. Therefore, in engineering design, it is not advisable to focus solely on the strength verification of individual connections. Instead, the comprehensive impact of connection stiffness, component mass distribution, and support positions on overall vibration characteristics should also be considered.

Based on the natural frequency, mode shape, and response results, the weak parts of the system are mainly concentrated in the thermo-sensitive component and its root connection. The connecting tube is an important path for transmitting external vibration to the thermo-sensitive component, while the bracket boundary condition affects the coupled vibration between the main body and the thermo-sensitive component. Therefore, the analysis should focus on the vibration transmission chain of bracket-main body-connecting tube-thermo-sensitive component.

5. Dynamic Response Analysis

In the dynamic response analysis, the thermal deformation excitation caused by temperature changes, the time-varying characteristics of connection contact stiffness, and the external random vibration excitation of the engine are comprehensively considered. The external excitation adopts a typical aeroengine random vibration test spectrum to reflect the wide-frequency vibration input in the actual working environment. Based on the system motion equation, the fourth-order Runge-Kutta method is used for numerical integration to obtain the acceleration responses of the detector body, connecting tube, thermosensitive components, and bracket in the x-direction, y-direction, and rotational direction.

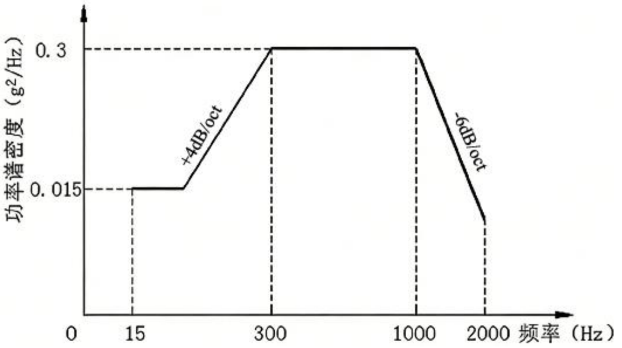

Figure 3: External Random Vibration Excitation Spectrum

The time-domain results indicate that the acceleration of each component exhibits wide-frequency random fluctuation characteristics, but the response amplitude varies with the vibration transmission path and local stiffness. The root mean square (RMS) accelerations in the x and y directions of the detector body are approximately 12g and 13g, respectively; those of the connecting tube are approximately 14g and 16g; those of the thermosensitive component are approximately 18g and 22g; and those of the bracket are approximately 11g and 12g. In terms of rotational direction, the RMS acceleration of the thermosensitive component is approximately 20g, second only to its y-direction response; the rotational response of the bracket is approximately 10.5g, which is relatively stable overall.

Table 2: Main time-domain response indicators of each component

x-direction RMS/g	y-direction RMS/g	Rotation RMS/g
12	13	16
14	16	15
18	22	20

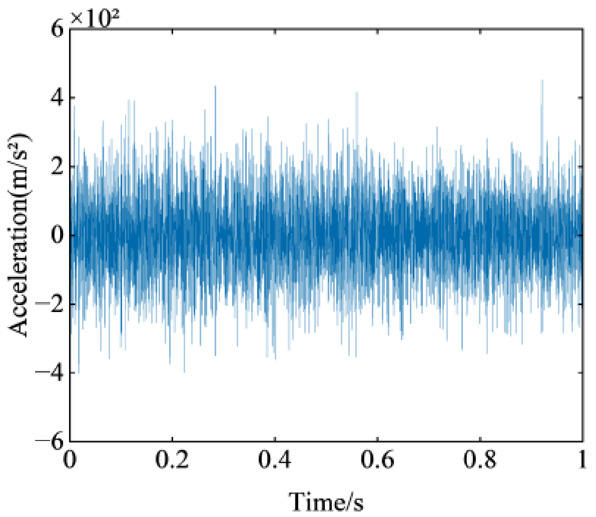

Figure 4: Time-domain dynamic response of the thermo-sensitive component

The frequency domain results indicate the presence of multiple local resonance peaks in the system. Notably, the 400~500 Hz frequency band repeatedly appears in the responses of the connecting tube and the thermosensitive component, reflecting the coupling between the bending and torsional modes of the connecting tube and the low stiffness characteristics of the thermosensitive component. Near 844 Hz, a strong narrow-band main peak is observed, primarily affecting the local responses of the detector body and the thermosensitive component. Considering the peak amplitude, recurrence frequency, and correspondence with external excitation, the 400~500 Hz and 844 Hz bands can be regarded as the main risk frequency bands of the system.

To further evaluate the loading level of key connection parts, the alternating bending stress of the dangerous section of the root weld was extracted based on a local flexible body model of the thermosensitive component. The calculation results show that the root section's alternating bending stress has an RMS value of 85.0 MPa, with a peak absolute value of 207.1 MPa and a peak-to-RMS ratio of 2.44. Its dominant frequency is concentrated around 400~500 Hz, which is basically consistent with the main response frequency of the thermosensitive component in the y-direction, approximately 463 Hz. This indicates a significant correlation between the alternating bending stress of the weld and the overall vibration response of the system.

From a dynamic perspective, the thermo-sensitive component is both the core sensing part and the component most sensitive to vibration. The connecting tube is the main path for transmitting vibration energy to the thermo-sensitive component. If the external excitation frequency in service is close to the risk band, sustained alternating loading may occur at the root weld, increasing the fatigue damage risk. Therefore, design and verification should focus on the y-direction response, rotational response, and root-weld stress state of the thermo-sensitive component.

6. Conclusions

Based on the lumped parameter method, this paper establishes a 12-degree-of-freedom dynamic model for the aeroengine temperature detector system. A local flexible-body model of the thermo-sensitive component is also introduced to analyze the inherent characteristics and dynamic response of the system. The main conclusions are as follows:

1) By modeling the detector body, connecting tube, thermo-sensitive component, and bracket as planar rigid bodies, and by equating welds, clamps, quick-clamps, and riveted connections to spring-damping units, the model can describe the overall motion of the system and the coupling relationship between components.

2) The first-order natural frequency of the system is 58.0 Hz, indicating overall torsional dominance. The low-order modes mainly reflect overall translational and mounting support effects, while the medium- and high-order modes gradually manifest as local vibrations of the connecting tube, thermo-sensitive component, and bracket.

3) Dynamic response analysis indicates that the thermo-sensitive component is the most significant response part of the system, with RMS accelerations in the y-direction and rotational direction of approximately 22g and 20g. The main risk frequency bands are concentrated around 400-500 Hz and 844 Hz. The root-weld alternating bending stress RMS is 85.0 MPa, indicating that this location is a potential fatigue weak area.

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