A quantitative evaluation method of aircraft wire performance based on infrared characteristic

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Abstract: As the "neural network" of airborne electrical system, the working state of aircraft conductor directly determines the reliability of the system platform. By the analysis of the performance degradation mechanism based on the thermal state model, it is concluded that local thermal stress is the common cause of apparent failure. The rated stable temperature rise of the wire is related to the working current value and the performance of insulating materials. The wiring mode is the actual influencing factor that determines the heat dissipation coefficient and surface area of the conductor. By analyzing the infrared characteristics of different wiring methods, a method is proposed to obtain the surface temperature spectrum to determine the thermal state. The relatively stable temperature rise and overflow rate are taken as the characteristic parameters, which can more accurately describe the sensitivity of wiring methods to thermal factors and realize qualitative analysis and quantitative evaluation. The feasibility of applying thermal imaging technology to the performance evaluation of aircraft electrical circuits is verified, and it can also provide reference for the active prevention and online diagnosis of line faults.

1. Introduction
As the carrier of transmission and distribution of electric energy and control signal, electrical circuit is the key to ensure the normal operation of power system.

With airborne system electrical equipment installation density increasing, lead to different ways of wiring in each frame, shuttle between tanks, the thermal stress concentration areas, accelerate the thermal aging, inevitably caused a significant reduction in the insulation performance, such as surface "hard brittle, mechanical strength and dielectric performance, etc., resulting in frequent failure.

At present, the research on the electrical circuit performance is mainly focused on the more economic significance of insulation aging and residual life research and other directions. Due to the differences of insulation materials of different products, targeted model tests are often carried out before installation. At present, there is no performance test research system with wide applicability in China.

Installed after the installation, environment and other factors is also the important factors that affect its performance, the fault caused by environment, in a different way and wiring, often after the system is abnormal, along the path for laying insulation offline artificial visual inspection, restricted by personnel maintenance experience, testing equipment, the fault is not easy to probe, for aircraft wire maintenance has brought great difficulties.

With the continuous development and improvement of infrared thermal imaging technology, especially the improvement of the accuracy of thermal imaging instrument, the temperature distribution of the detected part can be read out accurately by thermal imaging, and the internal
working condition and its soundness can be directly judged by analyzing and comparing the infrared characteristics. In addition to its advantages of small size, high efficiency and being suitable for large area online monitoring, it plays an increasingly important role in line detection and fault diagnosis[1-4].

Professor Sun Fengrui and Yang Li of Naval University of Engineering identified infrared technology’s capability of fault diagnosis for mechanical and electrical equipment and set the evaluation indexes of infrared technology to the fault diagnosis. Meanwhile, they put forward that fault diagnosis of mechanical and electrical equipment using infrared technology is to accurately obtain the temperature distribution of the device under test, as well as the temperature or temperature rise of fault point, which could judge whether the device is faulty and identify the cause of the problem, influence factors and the failure degree[5-7].

In this paper, the experimental platform is designed and built according to the actual wiring mode of aircraft wire.

In a certain working state, the experimental study was carried out on the different laying modes of the wire. The selected parts were monitored online by the infrared thermal imager, the infrared characteristics of the temperature field were analyzed, and the characteristic parameters were extracted. The typical parts were analyzed and processed, and the online diagnosis and prevention were explored.

2. Aircraft wire thermal state model
The wire in the airborne electrical network are often bundled into bundles and installed in narrow compartments in different wiring ways in the actual path of the trend. The thermal effect will be generated when the conductors run under a certain current flow, and the thermal state of the conductors is ‘adapted to local conditions’.

Wires through the insulation materials, inner core wire wrapped, laying path to transfer heat, its temperature is usually higher than the environment temperature[8], after a period of time to reach thermal equilibrium, considering the actual working status of the wire, conductor thermal state affected by many factors, it is difficult to accurately calculate, the related influence factors to determine the general approximate values by experimental method.

Normally most of the heat generated by the conductor (80% ~ 90%) is dissipated by convection, almost all the remaining heat is dispersed by radiation[9-11]. The surface of the insulation layer of the wire and the laying environment conduct natural convection heat transfer. When the heat and heat dissipation reach the heat balance, the temperature distribution tends to be stable[12].

Ignoring the effect of temperature on the conductor's dc resistance, when a current I passes through the wire, electrical energy is converted into heat energy[13].

According to joule's law, the heat generated by current I in time dt is:

\[ Q = I^2 R dt \]

Where Q is calorific value (joule), I is load current (ampere), and R is wire resistance per unit length (ohm).

Part of the heat generated by dt over a period of time is used to heat the wire, and its value is GC; The other part radiates heat into the surrounding medium in the form of heat, and its value is \( SK(\theta - \theta_0) dt \). The heat balance equation of the wire in the heating process is:

\[ I^2 R dt = KS(\theta - \theta_0) dt + GCd\theta \]

Where G is weight of wire, C is specific heat capacity, \( \theta_0 \) is temperature of the surrounding medium of the conductor, \( \theta - \theta_0 \) is temperature rise of wire, S is cooling surface area of wire, and K is heat dissipation coefficient.

By solving this differential equation, the general solution can be obtained:

\[ \theta = \frac{I^2 R}{KS} + \theta_0 - Ae^{\frac{R}{S}} \]
Where $T = \frac{GC}{KS}$ is the heating time constant of the wire,

When $t=0$, $\theta=\theta_0$, then,

$$A = -\frac{I^2R}{KS}$$

The particular solution of the differential equation is:

$$\theta = \theta_0 + \frac{I^2R}{K_S} \left( 1 - e^{-}\frac{t}{T_0} \right)$$

When the stable temperature value is fixed, it is the allowable temperature value of the wire under a specific wiring harness and wiring mode, which is related to the working current value and the performance of insulating material.

In practical work, the wiring mode is the actual factor that determines the heat dissipation coefficient and surface area of the conductor. The rated stable temperature value of the wire is more determined by the actual situation of its wiring. The infrared thermal imaging technology uses the infrared radiation effect to obtain the surface temperature spectrum of the wire in real time, and then determines its thermal state.

3. Experimental scheme

The selection of the experimental scheme should consider the effectiveness of the implementation of the test platform technical means, and the selection of the measurement point should consider the actual installation of the airborne electrical circuit; In view of the wiring mode of airborne electrical circuits prone to local thermal stress, the test selects multiple measurement points from the aspects of manifold, allowance processing, line protection and trend, and properly disposes external parameters to obtain experimental data.

3.1 setting of external parameters

This experiment USES measuring instruments for the infrared thermal imager, models for FLUKETi400, plus or minus 2°C or 2% accuracy. Emission rate for epsilon=0.9, the environment temperature $t_0 = 15^\circ C$~$19^\circ C$, air humidity is 50%, interior does not consider solar radiation, wind and other external environment factors; Test sample selection of 0.75 mm copper core PVC heat wire, the nominal pressure values 450/750 V, resistance around 0.01 Ω/m, external rated working voltage of 27.5 V.

In view of the large number of operating current of the electrical equipment on board within the range of 5 ~ 7A, which usually does not exceed 10A, the working current (applied stress) in the experiment is adjusted by the power sliding rheostat, the specific given value is shown in table 1.

| Group status | state 1 | state 2 | state 3 | state 4 | state 5 | state 6 | state 7 |
|--------------|---------|---------|---------|---------|---------|---------|---------|
| Working current (applied stress) | 0.5     | 1.5     | 2.7     | 3.5     | 4.5     | 5.5     | 8.8     |

3.2 selection of measurement points

The selection of measurement points in the experiment should consider the actual installation of airborne electrical circuits, which can reflect the thermal state characteristics of the measured points and facilitate the acquisition of thermal characteristic parameters.

A certain interval should be kept between adjacent measuring points to reduce the influence of infrared radiation and external thermal conditions.

The sensitivity of the relative "heat" factor of the measuring point is taken as an important reference for selecting the measuring point. If the relative sensitivity of a measuring point is relatively high, it indicates that the measuring point can significantly reflect the actual working state of the
wiring.

Based on the comprehensive consideration of the actual laying situation of airborne electrical circuits and the requirements for measuring points, this experiment selected 4 kinds of bus-bar mode, 3 kinds of residual treatment mode, 2 kinds of protection mode and 6 kinds of different trend for specific analysis, the specific situation is shown in table 2.

### Table 2. wiring methods in the experiment

| Number | Measuring point | Wiring method | Wiring position | Quantity | Description of measuring points in special handling mode |
|--------|-----------------|---------------|-----------------|----------|---------------------------------------------------------|
| 1      | 1               | Junction line | Junction of one end of wire harness | 12       | Wiring harness 1, 2 and 3 wire harnesses on one side of the wiring terminal, 6cm away from the wiring terminal |
| 2      | 2               | Junction line | The junction line after the junction line with other wiring harnesses is treated | 3, 4     | Superfluous wire after processing |
| 3      | 3               | Junction line | The junction of two groups of wire harness convergence lines | 4, 3     | The confluence of two beam lines with different trends |
| 4      | 4               | Junction line | Junction of one end of wire harness | 7        | Between 4 and 5 wires near the terminal of the junction, from the end of the confluence to the 3cm |
| 5      | 5               | Residual processing | A large number of residual wires processing | 4        | Residual treatment overlap binding place |
| 6      | 6               | Residual processing | A small amount of residual wire processing | 5        | Close to the wiring terminal manifold, the bending inner diameter is about 4.20cm |
| 7      | 7               | Residual processing | Residual treatment of narrow spaces | 5        | At the initial confluence of residual processing, the bending inner diameter is about 1.14cm |
| 8      | 8               | Protect       | High temperature bandage belt main support | 5        | |
| 9      | 10              | Protect       | High temperature protective tape binding and main support | 5        | |
| 10     | 11              | Trend         | Wire twisting in harness | 5        | |
| 11     | 12              | Trend         | To be strapped with a metal wave-proof sleeve. | 3        | |
| 12     | 13              | Winding       | Large angle bending of wire harness | 5        | Bend the wire harness at a large Angle, and the bending inner diameter is about 0.71cm at the overlapped |
| 13     | 15              | Winding       | Large angle bending of single wire in wire harness | 3        | Overlapping binding at residual treatment site |
| 14     | 16              | Trend         | Wire harness without strapping | 3        | Bundling position near the confluence line |
| 15     | 17              | Fixed         | Equally spaced wire harness with auxiliary support | 5        | Spacing 20mm |

### 3.3 experimental process

Considering the influence of the thermal radiation generated by the long time working of the infrared thermal imager on the test circuit, the sample images were acquired at an interval of 20min in the experiment. Considering the actual situation of the flight mission, the continuous power on time is generally 2 hours, and the specific process is shown in figure 1.
4. **Infrared characteristic analysis**

Thermal imaging figure in figure 2 (a) at the point of the original figure, take 250 * 400 drawing 3D numerical simulation image, as shown in figure 2 (b), allowance for the 3D numerical simulation of the image processing installation, Overlapping position of wire harness in residual processing are remarkably high temperature, in the small radius bending place, As a result of the dispersal of the confluence at the relatively low temperature, the highest temperature for its remit line overlap;

The numerical simulation results well showed the actual shape of the wiring, which was in good agreement with the thermal imaging results, and the temperature level was clear, reflecting the temperature distribution characteristics well.

![](image1.png)

(a) infrared thermal image (original image) (b) numerical simulation image (Two views)

Figure 2. Comparison of infrared thermal imaging and numerical simulation of the residual treatment site.

4.1 **peak temperature in the temperature field**

Figure 3 to figure 5 compare the changes of the maximum temperature value (peak value) of the temperature field in different wiring modes within the window with the collection time under partial working conditions.
Figure 3. \(I = 0.5\) A, \(T_{\text{max}}\) comparison of the maximum temperature value at some measuring points.

As shown in figure 3, when \(I = 0.5\) A, the highest temperature of each measurement point in \(t_1 \sim t_7\) slowly rise over time and the temperature changed less than 1°C. While \(t_4\) is the measurement inflection point, and the temperature rise rate of the measurement point is relatively fast between time points \(t_1\) and \(t_4\). And \(t_4\) and \(t_5\) temperature began to stabilize after moment, each measuring point temperature difference between time \(t_1\) and \(t_7\) has nearly 3°C.

Figure 4. \(I = 2.7\) A, \(T_{\text{max}}\) comparison of the maximum temperature value of some measurement points.

As shown in figure 4, when \(I = 2.7\) A, the temperature of each measurement point rises rapidly. Compared with the pre-sequence state, the temperature of each measurement point tends to be stable and moves forward further. With the increase of electrification time, the overall trend of each measurement point began to show a certain temperature difference.

Figure 5. \(I = 5.5\) A, \(T_{\text{max}}\) comparison of the maximum temperature value at some measuring points.

As shown in figure 5, \(I = 5.5\) A. After \(t_2\), the temperature of each measurement point rises rapidly and tends to be stable. Electricity increases with time, each measuring point temperature difference is
more apparent, overall trend part of the measurement point of maximum stable temperature has more than 40 ℃.

Figure 3 to figure 5, each measuring point temperature stable point by t₁ advance gradually to t₂, stable temperature from 20 ℃ to 60 ℃, survey points 6, 7, 13, for example the same wire of different parts of the path, the rest of the amount of processing mode, especially the wire bending diameter there is a certain difference, the temperature of the measurement point 6 is higher, measurement point 7, 13, the temperature is relatively consistent, allowance of different sensitivity to the thermal stress in different processing ways.

The length of the wire harness overlaps at measuring points 5 and 7 is consistent. The "eight-character knot" method is adopted at measuring points 5 to carry out residual treatment, and the thermal stress is relatively dispersed. The measurement point 6 is treated by "small residual coil method", and the thermal stress is relatively concentrated, and the cooling area is smaller than 5.

The measurement point 7 was tied up, while the measurement point 13 was not tied up. The temperature display was basically the same. The overlapping areas of measuring points 6 and 7 are basically the same. Although the curved inner diameter of measuring point 6 is larger, the temperature shows that measuring point 6 is much higher than measuring point 7. The bending diameter of wire harness and its allowance treatment method have obvious effect on thermal stress and are important factors affecting the temperature rise of wire.

4.2 relatively stable temperature rise

![image]

(a) trend diagram  
(b) gradient spectrum

Figure 6. comparison of the relative stable temperature rise Ts values of some measurement points under different conditions

After a certain period of time, the maximum temperature of each measurement point tends to be stable, and the characteristic parameter is the relative stable temperature rise, that is, the difference between the maximum temperature value that tends to be stable and the initial maximum temperature value is taken as the value of the relative stable temperature rise Ts, Ts= Tmax-T0, (Tmax, the maximum temperature value that tends to be stable in a certain state;T0, the maximum temperature value at the initial moment of a certain state), and the relative stable temperature appreciation of some measurement points in different states is selected for comparative analysis, as shown in figure 6. State 4 is the inflection point of curve change. Before state 4, the relative stable temperature rise of each measurement point fluctuates within a certain range with the increase of thermal stress and tends to be stable basically. Between state 3 and state 5 (when the current value is given as 2.7A≤I≤4.4A), the relatively stable temperature rise of some measurement points has a small fluctuation, which should be the exercise period of the relatively stable temperature rise of the measurement points. After state 4 (when the current value I > 4.4A is given), the measurement point is more sensitive and shows an increasing trend with the increase of thermal stress, and the relatively stable temperature value of measurement point 5 is the highest. The sensitivity of different wiring modes to thermal stress is different under different working current.
4.3 overflow rate of temperature rise

![Diagram](a) trend diagram (b) gradient spectrum

Figure 7. comparison of partial measurement points with $\lambda_s$ value under different conditions

Under different operating currents, the relatively stable temperature rise of each measuring point is different, which shows the sensitivity of different wiring modes to thermal factors. The working current or wiring mode leads to excessive thermal stress value exceeding the rated thermal load of the wire, which is easy to cause wire performance degradation. The characteristic parameter is the ratio of the relatively stable temperature rise $T_s$ to the rated maximum stable temperature rise $T_{em}$, denoted by $\lambda_s = T_s / T_{em}$. Figure 7 is the trend diagram and gradient spectrum of the temperature rise overflow rate at some measuring points under different states of $\lambda_s$. State 4 is the watershed of curve change. Before state 4, the temperature rise overflow rate at each measuring point of lambda s fluctuates within a certain range with the increase of thermal stress (working current) and tends to be stable basically. After state 4 (when the current value $I > 4.4A$ is given), the measurement point is sensitive to the increase of thermal stress and shows an increasing trend, which has exceeded the general thermal capacity of the wire. The heat resistance of different wiring modes to thermal stress is different under different working current.

5. Conclusion

This paper presents a quantitative evaluation method of aircraft line performance based on infrared characteristics. Under the action of different working currents, the circuit is electrified. The "thermal" information is extracted from the parts where the thermal stress is relatively concentrated by the infrared thermal imager to form the temperature spectrum. It is believed that the highest temperature in the temperature field can accurately locate and track the monitoring parts. Due to the difference in the sensitivity of different laying modes to thermal factors, the relatively stable temperature rise $T_s$ and temperature rise overflow rate $\lambda_s$ are defined and used as the characteristic parameter, which can reflect the difference in the heat resistance of wiring modes to thermal stress to a certain extent.

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