Boundary Layer Transition Measurement Flight Test Based on Infrared Image Technique

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Abstract. According to the requirements of boundary layer transition detection measurement flight test, the study on the detection technique of infrared thermal image in real flight conditions was carried out. In this paper, the basic principle of infrared measurement technique was introduced firstly. Through the analysis of the main factors, such as emissivity, radiation incidence angle and temperature difference between the measured object and environment, the test means were determined, which includes surface treatment, infrared light path adjustment, solar radiation and internal heating of tested parts. Then the whole flight test method of boundary layer transition measurement was designed, including selecting test object and test instrument, determining test procedure and image processing procedure, and giving transition location criterion. Finally, the validity of this flight test method was demonstrated through testing results, the research of which would be helpful and meaningful in boundary layer transition measurement.

1. Introduction
Drag reduction has always been one of most concerned problems in aviation, which is more significant for increasing civil aircraft efficiency. Recent years, the technology of drag reduction in laminar flow has attracted more and more attention, especially natural laminar flow wing design and hybrid laminar flow control method, which would be one of most important way of drag reduction in future civil aircraft design.

In order to demonstrate the effect of hybrid laminar flow control and laminar wing design in flight condition, flight test should be design and conducted. In early stage of flight test for laminar aerodynamic characteristics, boundary layer transition is frequently detected by oil-flow method[1] or sublimation techniques[2]. Measurement results of these methods may be affected by the visualization material, especially the operation of sublimation techniques is hard to ensure test duration and difficult to apply and control in flight test. Comparing with other test method, Infrared image technique has its advantages as one non-contact global measuring method, such as no interference to flow, high temperature resolution, high space resolution and easy operation. Infrared image technique has been conducted flight test in test aircraft[3-6], like LFU 205,VFW614/ATTAS, Do 228,Fokker 100, but boundary layer transition application was only implemented in wind tunnel in China[7-9]. As civil aircraft program like C919 is proceeding, it is urgent to demonstrate drag reduction technique in laminar flow and carry out boundary layer transition flight test.

In this paper, infrared image technique was applied in boundary layer transition flight test to explore transition location during real flight conditions. Firstly, the article introduces the principle of measurement for boundary layer transition using infrared image techniques. And the main factors
affecting boundary layer transition are analyzed, such as infrared emissivity, radiation incidence angle and temperature difference between test object and background environment. Moreover, certain solutions are proposed, including matted painted on surface of test object, infrared ray direction adjusting, solar radiation and internal heating, which are useful for boundary layer transition location exploration in flight test demonstration. Furthermore, flight test method is introduced and results are analyzed respectively. Through research of boundary layer transition using infrared image technique, an integrated theory of transition flight test has been established, which is helpful and meaningful for aircraft design.

2. Principle of measurement

2.1 Skin friction and heat transfer

When aircraft fly in the atmosphere, boundary layer transition would be caused due to instability mechanism in wing surface and boundary layer was divided into laminar and turbulent flow, which are two totally different flow form. Smooth and continuous laminar flow move along main flow direction, and do regular and stratified movement, while the turbulent flow mix unordered and violent. Hence, under the same condition, the heat transfer of turbulent is greater than laminar. According to Reynolds analogy, the heat transfer coefficient $\alpha$ is determined by following parameter in a simplified form[10]:

$$\alpha = \frac{1}{2} C_f \frac{U \lambda}{\nu}$$

Where, $C_f$ is the skin friction coefficient, $U$ is the local velocity, $\lambda$ is the heat conductivity of the fluid and $\nu$ is the kinematic viscosity.

For the civil aircraft design, $\lambda$ does not change with pressure. The formula (1) explains that heat transfer in a laminar boundary layer is small since skin friction coefficient is small. The surface temperature in laminar boundary layer could only be transferred to the temperature of free flow slowly. However, ignoring some transition range conditions, skin friction coefficient in turbulent boundary layer would increase dramatically compared with laminar boundary layer, and heat transfer is much increased. Hence, turbulent boundary layer would absorb heat quickly from outside free flow and reach the temperature of free flow.

In a certain amount of time, the temperature of laminar boundary layer is higher than turbulent boundary layer. Through measurement, transition location of boundary layer could be estimated from the temperature difference showed in temperature distribution of test zone.

2.2 Infrared image technique

Infrared image technique is one non-contact passive measuring method. The principle of Infrared image technique is using that the object in natural world which temperature is higher than absolute temperature will emit infrared radiation automatically, which can be used to estimate temperature distribution and temperature of test target.

Infrared image technique was applied in boundary layer transition measurement, and the principle of measurement mechanism is that heat transfer would cause surface temperature change of test object when air flow pass the surface of measured piece. When the flow past the wing surface is transferred from laminar to turbulent, heat transfer is different between flow and surface due to different status of flow and temperature of surface would be changed.

Through Infrared detection equipment Infrared radiation signal emitted by test object was converted to electric signal according to infrared photoelectric effect. After a series of transformation, like signal amplification, setting standard black-body, correction and calibration[11], the electrical signal was converted to visual signal so that infrared image system could stimulate spatial distribution of surface temperature of test object. After system processing, infrared image visual signal is shown in gray scale or pseudo-color, which is called infrared image. Hence, temperature field of test object
could be obtained directly by infrared image which shows measured temperature of test object in real time and boundary layer location could be estimated by temperature difference.

3. Influence factors analysis

3.1 Radiation coefficient

Boundary layer transition based on infrared image technique needs to explore infrared radiation of test object and background environment. So the definition of radiation coefficient is that the absolute value of exitance difference between test object and background environment divides the maximum of radiation exitance of test object and background environment \[ [12] \]. The radiation coefficient can be described as follows [12]:

\[
C = \frac{|M_T - M_B|}{\max \{M_T, M_B\}}
\]  \hspace{1cm} (2)

Where \( C \) is radiation coefficient, \( M_T \) is radiation exitance of measured piece, \( M_B \) radiation exitance of background environment.

From Stefan-Boltzmann’s law, effective radiation exitance of test object and background can be expressed in following form:

\[
M_T = \varepsilon_T \sigma T_T^4 + (1 - \varepsilon_T) \sigma T_B^4
\]  \hspace{1cm} (3)

\[
M_B = \varepsilon_B \sigma T_B^4 + (1 - \varepsilon_B) \sigma T_T^4
\]  \hspace{1cm} (4)

where \( \varepsilon_T \) is emissivity of test object, \( \varepsilon_B \) is emissivity of background environment, \( \sigma \) is Stefan-Boltzmann’s constant, \( T_T \) is surface temperature of test object, \( T_B \) is temperature of background environment.

Assuming that temperature of background environment is constant, using equation (3) and (4), formulation (2) can be rewritten as follows:

\[
C = \frac{4 \Delta T + \left( 1 - \frac{T_B}{T_T} \right)^4 \varepsilon_T \varepsilon_B}{1 + \frac{1 - \varepsilon_T}{\varepsilon_T} \left( \frac{T_B}{T_T} \right)^4} \frac{\Delta \varepsilon}{\varepsilon_T}
\]  \hspace{1cm} (5)

Where \( \Delta T \) is temperature difference between test object and background environment, \( \Delta \varepsilon \) is emissivity difference of test object and background environment.

From equation (5), it can be seen that the main factors affecting radiation coefficient are temperature difference between test object and background environment and infrared emissivity difference between test object and external environment.

3.2 Emissivity and Radiation incidence angle

Emissivity is the ratio of radiation energy of object to that of blackbody in theory at a certain temperature, which falls between 0 and 1. During flight test of boundary layer transition exploration, emissivity of atmospheric environment could not be changed generally, and emissivity of test object is related to material of object, surface condition, reflectivity and opacity. Among these factors, material of object is the most important factor affecting emissivity and oxygenation efficiency, surface treatment and surface contamination affect emissivity of test object too. In general, emissivity of nonmetallic and material with low surface gloss and low opacity is higher than metallic and material with high gloss and high transparency.

Meanwhile, energy distribution of infrared radiation is totally different in different direction, so emissivity \( \varepsilon(\theta) \) was introduced for further expression, which is defined by

\[
\varepsilon(\theta) = \frac{L(\theta)}{L_n}
\]  \hspace{1cm} (6)
Where $\theta$ is radiation incidence angle, $L(\theta)$ is directional radiation intensity which is tilted $\theta$ relative to normal radiant surface, $L_0$ is directional radiation intensity of black-body at the same temperature. 

For nonmetallic material, directional emissivity changes a little when $\theta=0^\circ \sim 60^\circ$ and directional emissivity decreases obviously when $\theta$ exceeds $60^\circ$. For Metallic material, directional emissivity has a little change when $\theta$ varies from $0^\circ$ to one certain angle, which is relative with material, and then directional emissivity decreases rapidly when $\theta$ increases. But When $\theta=0^\circ \sim 90^\circ$, $\xi(\theta)$ is rather small and could not achieve the requirement of infrared emissivity ($\xi(\theta)>0.5$). Directional radiation properties of nonmetallic and metallic surface are shown in figure 1.

Hence, considering flight test condition, there are certain actions that could be taken during flight test. Firstly, under the premise of structural strength during research process of test object, Nonmetallic with high infrared reflectivity like composite material could be used as surface structure material. If test object is metallic or the surface is painted smoothly, black paint with high infrared reflectivity should be chosen for spray. If infrared ray direction could be selected properly, small radiation angle of incidence could help get high radiation intensity.

3.3 Temperature difference

Temperature difference between test object surface and background environment, could be obtained through certain measures such as changing flight altitude, solar radiation and internal heating.

1) changing altitude. flight height is changed based on the temperature gradient of different pressure heights. Therefore, temperature difference could be obtained through changing flight height where heat exchange could be made through temperature changing of external free flow. The advantage of this measure is requiring no additional equipment, but this measure demands that the range of altitude change greatly to acquire larger temperature difference. And the aircraft changes altitude during flight, heat of aircraft transfer to atmosphere through thermal transmission, and finally effect is not ideal by this kind of measure to obtain temperature difference.

2) External solar radiation heating. External solar radiation heating through heating surface of test object by solar radiation makes the temperature of surface increase, and temperature difference is obtained. The advantage of external heating is same with that of changing altitude. But image could not be recognized due to overexposure, which caused by sunlight reflecting off the lens of infrared image camera. When solar radiation intensity is not enough, such as clouds, temperature difference could not be got. Meanwhile, it is necessary to paint surface dark in order to acquire better endothermic effect.

3) Internal heating. Generally, internal heating is laying heating film or heater strip in interior surface of test object to achieve quick heating. Surface temperature of test object increases due to ohmic heating, so temperature difference is formed. The advantage of internal heating is that temperature can be controlled quantitatively by pilot or engineer, but the disadvantage is that cost and workload of design and modification are increasing dramatically. Meanwhile, it is worth noting that
transition location may be affected by convection heat exchange between external free flow and test object. According to [9], there is no influence on transition location when temperature difference is controlled within 20°C.

4. Conducting Flight test

4.1 Test object
Test aircraft is one low-winged and tail mounted engine business aircraft and the middle of left wing was used as the test area which was shown in figure 2.

![Figure 2. Boundary layer transition measurement region](image)

**Table 1.** Flight test condition

| Pressure altitude | Mach | Reynolds number | no heating measurement | changing altitude | solar radiation heated | Internal heated |
|-------------------|------|-----------------|------------------------|-------------------|------------------------|-----------------|
| 7000m             | 0.65 | 1.595×10⁷       | -                      | -                 | -                      | √               |
| 7000m             | 0.60 | 1.472×10⁷       | -                      | -                 | -                      | -               |
| 7000m             | 0.55 | 1.347×10⁷       | √                      | -                 | -                      | √               |
| 7000m             | 0.55 | 1.347×10⁷       | -                      | √                 | -                      | -               |
| 7000m             | 0.55 | 1.347×10⁷       | -                      | -                 | √                      | √               |
| 7000m             | 0.55 | 1.347×10⁷       | -                      | -                 | -                      | -               |
| 6500m             | 0.65 | 1.682×10⁷       | -                      | -                 | -                      | √               |
| 6500m             | 0.60 | 1.553×10⁷       | -                      | -                 | -                      | -               |
| 6500m             | 0.55 | 1.424×10⁷       | -                      | -                 | -                      | √               |
| 6000m             | 0.65 | 1.766×10⁷       | -                      | -                 | -                      | -               |
| 6000m             | 0.60 | 1.637×10⁷       | -                      | -                 | -                      | √               |
| 6000m             | 0.55 | 1.491×10⁷       | -                      | -                 | -                      | -               |

The material of wing cover in test region is aluminum alloy and the surface of wing cover is white, polished and painted, the chord length of middle test zone is 2.1 meter. The span-wise range is 1.91 to 3.21 meters between test zone and wing-root and the leading edge sweep angel is 9°. In chord position x/c=0%~33% of test zone, the surface was painted black coating with high infrared emissivity. In boundary layer test zone besides wingtip and wing-root, aluminum foil was pasted as reference marks at intervals of 5 percent of chord length of the wing, which are x/c=3.5%, 8.5%, 13.5%, 23.5%, 28.5%. All of these marks are used for infrared image geometric coordinate transformation and transition location identification during data processing.

4.2 Testing instrument
One FLIR A655cs infrared image camera was mounted besides cabin window, shown in figure 3. The optical field of view is 45°×45°, the measurement accuracy of absolute temperature is 0.1°C, the range of measurement is -40°C to 650°C, the range of response wavelength is 7.5μm to 14μm, Pixel resolution is 640×480.
4.3 Testing Method
Three flight levels were chosen between 6000 and 7000 meters, which is pressure altitude. Three velocities were selected between 0.5 and 0.65 Mach Number. The range of Reynolds number is $1.3 \times 10^7$ to $1.7 \times 10^7$. The measurement of boundary layer transition was conducted in steady level flight, and the whole flight conditions are shown in table 1. During flight test, aiming at temperature difference between test area and background environment, the following steps are taken respectively:

1. No heating measure: test area of wing under shadow of fuselage and no sun radiation.
2. Altering flight altitude: test aircraft climbs to the altitude which is over than scheduled test height, then descend rapidly to determined altitude. Test area under shadow of fuselage and no sun radiation.
3. Sun radiation: through changing heading of aircraft, let test area leave shadow of fuselage and adopt sun radiation.
4. Internal heating: test area under shadow of fuselage and no sun radiation, using heating unit mounted inside leading edge to heat test area for 30 seconds, the heating location is about $x/c=0\%$~$8\%$.

4.4 Infrared image processing method
The whole process of infrared image is shown as follows. The original infrared images were obtained from flight test, which were given normalized treatment. Then infrared image gray field was calculated, and the range of gray field is 0 to 1. Furthermore, in order to eliminate lens distortion, geometrical deformation was given to infrared images so that sweep-back wing image could be transformed to rectangular wing image and redundance of image was cropped for next step. Furthermore, temperature gradient field was calculated based on infrared images and each transition location of span-wise section was estimated according to the extreme value of temperature. Statistics are made for all transition locations of span-wise section, and most precise location are indicated based on curve of maximum probability density. The procedure of infrared image processing is shown in figure 4.

4.5 Transition location measurement accuracy
In order to verify the accuracy of boundary layer transition measurement results, One trip strip was applied on the surface used rough strips with 0.1mm thick, 1.2mm diameter and 2mm at interval at $x/c=3.5\%$ and one third span location near wing-let, which is based on the acquired natural transition location $x/c=7.4\%$~$7.8\%$ in measured region. After this measure taken, boundary layer transition was happened in this region and the location is $x/c=3.5\%$. In the subsequent processing of infrared image,
transition location measurement accuracy could be given on the basis of difference between $x/c=3.5\%$ and indicated transition location estimated by measured transition location accuracy zone.

5. Results analysis

The pressure height of the flight test is 7000m and Mach number of the flight test is 0.55, the flight test is conducted under the condition of no heating measurement, changing flight height, sun radiation heating and using the leading edge deicing equipment to heat the measured region $x/c=0\%$–$8\%$ respectively, the results under these four conditions are given by figure 5-figure 8. Figure 7 also shows the indicated transition position based on the accuracy of the transition position measurement.

From figure 7, it can be seen that the measured fixed transition position under accuracy region of the transition position measurement is $x/c=3.12\%$. Meanwhile, the fixed transition position of other flight conditions is calculated, of which the difference value with the forced transition roughness strip is $0.2\%$–$0.4\%$. The results show that it’s credible to measure the transition position by infrared image technique.

According to figure 5-figure 8, it can be concluded that under the certain flight condition that pressure height is 7000m and the Mach number is 0.55, the extreme value of the temperature of the span-wise profile is scattered under non heating measure condition, and the transition location can’t be given by statistics. When the flight height is changed, infrared image can be used to identify the temperature boundary between laminar boundary and turbulent boundary before and after transition happened. Although some extreme values of temperature of the span-wise profile are scattered, the transition location can still be given as $x/c=7.44\%$. Under solar radiation condition, temperature difference can be identified by infrared image, the transition location can be given as $x/c=6.30\%$. In the measured region, there are three extreme values of temperature of span-wise profile which are close to leading edge, and it’s probably induced by the contamination of the measured object’s surface. Under the condition of leading edge heating, the radiation contrast of infrared image is obvious and clear, where the extreme value of temperature of the span-wise profile is uniform, and the transition position is given as $x/c=7.69\%$. Under the condition of heating the inside of the measured object, the heating power can be calculated by Newton cooling law which is given by equation (7); Temperature difference is set as $5^\circ C$ and area power is set as 400W/m$^2$, the heating power is estimated by reference[10].

\[
Q = \frac{\bar{h}A(T_0 - T_s)}{L} = 2 \frac{k}{L} \sqrt{\frac{Re_L}{0.332 Pr^{1/3}}} A \Delta T
\]

Where $Q$ is heating power ; $\bar{h}$ is convective heat transfer coefficient; $A$ is the area of the measured region; $T_0$ is the temperature of background environment; $k$ is thermal conductivity; $L$ is characteristic length of the heat transfer surface; $Re_L$ is Reynolds number corresponding to the characteristic length; $Pr$ is Prandtl number; $\Delta T$ is the temperature difference between the surface of the measured object and background environment.

![Figure 5](image)

*Figure 5. Hp=7000m, M=0.55, no heating*
6. Conclusions
Considering the problem of the application of infrared image technique on boundary layer transition measurement in real flight conditions, the main influence factors, such as radiation coefficient, radiation incidence angle, temperature distinction of measured object and background environment, are analyzed firstly in this paper. Then the flight test is designed and established, and according to flight test data analysis, the following conclusions can be given: in flight test conditions, by spraying the black paint on surface, adjusting reasonably infrared light path and heating the measurement object, infrared image technique can be used for flight test of boundary layer transition measurement, results of measured transition position are credible. Under the same flight condition, it is suggested that heating test object inside is the best method to get radiation contrast effect in order to get temperature difference of the measured object and background. In practical engineering application, calculation equation of heating power or area power can be used to calculation or estimate the needed heating power.
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