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STUDY ON THE METHOD OF DETERMINING SKIN WAVINESS REQUIREMENT OF CIVIL AIRCRAFT

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Abstract

Skin wave is one of the main deviations in aircraft manufacturing, which will directly affect aircraft performance. Therefore, it is necessary to put forward appropriate waviness requirements to control the manufacturing deviation. In this paper, The skin shape of civil aircraft is measured to get the wave shape, and the characteristic parameters of wave are studied. Based on Carmichael's criterion, the relationships between wave length and wave height of different seat class civil aircraft are obtained, the ranges of waviness for different seat class civil aircraft are given, and the method of determining of general and special waviness requirements is proposed. By comparing the calculated results of waviness with the actual waviness requirements of a typical civil aircraft, it proves that the method of determining waviness requirement is valid. This method gives a reference for the formulation and improvement of waviness requirements of civil aircraft.

Keywords: civil aircraft, waviness, three-dimensional photogrammetry method, Carmichael’s criterion

1. Introduction

In the process of aircraft manufacturing, there will be various kinds of deviations compared with the theoretical shape. The unexpected wave is one of the main types of deviations, which makes the ideal shape less smooth. The ripple of the aircraft skin will affect the performance of the aircraft. For example, it will not only induce airflow separation in the airflow acceleration zone , increasing the flight drag, but also affect the measured value of atmospheric sensors, and then affect the indication of airspeed and altitude. Therefore, it is necessary to put forward the requirement for the wave size of aircraft skin to control manufacturing deviation.

In the case of no large overall deviation and step difference of aircraft surface, the manufacturing deviation of skin is generally shown as the unexpected fluctuation phenomenon near the theoretical shape. The measurement concept of the unexpected fluctuation phenomenon is called waviness, which is defined as the ratio of wave height to wave length[1] (h/λ in the figure 1).

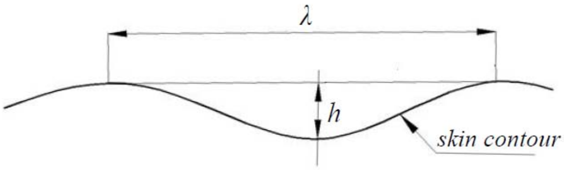

Figure 1 –Definition of waviness.

In order to study the method of determining the waviness requirement, it is necessary to study the characteristic parameters of the wave firstly, and then find a suitable calculation method of the waviness requirement based on the parameters of the wave.

2. Characteristic Parameters of The Wave

2.1 Sample Acquisition

In this paper, the actual shape data of aircraft skin is obtained as the research sample by using three-dimensional photogrammetry method. Three dimensional photogrammetry is a kind of measurement method that uses optical camera to obtain the image of the object, and then processes the image to obtain the shape, size and other information of the object.

At present, the commonly used three-dimensional photogrammetric systems are V-STARS, MPs/M, etc. Using three-dimensional photogrammetric system to measure the aircraft surface is extremely fast and convenient, and the measurement accuracy can be better than 0.01mm, which is sufficient for the study of waviness[2].

In this paper, typical components of aircraft, such as wing, fuselage and tail, are selected, and the skin shapes of these components are measured by three-dimensional photogrammetry system. The measurement results are dense point-clouds, and its image rendering effect is shown in Figure 2.

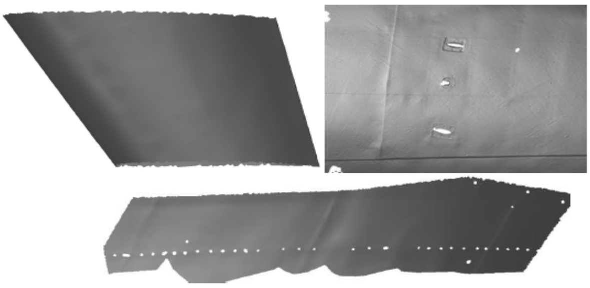

Figure 2 –Samples obtained by 3D photogrammetry method.

2.2 Characteristic Parameter Extraction

Because the definition of waviness is two-dimensional, it is necessary to sample from the three-dimensional measurement results. Therefore, some processes need to be carried out. First of all, the measured data is pre-processed to remove bad points and the points of useless areas, and the triangle mesh surface is generated to get the measured skin surface, so as to identify the wave easily. Secondly, the best fit function in the digital shape editor (DSE) module of CATIA software is used to fit the measured skin surface to the theoretical surface. Then, some sections are selected for two-dimensional sampling. The measured skin surface and the theoretical surface are intersected by the same section to obtain the contours. The wave shape is obtained by comparing the measured skin contour with the theoretical contour. The data sampling process is shown in Figure 3.

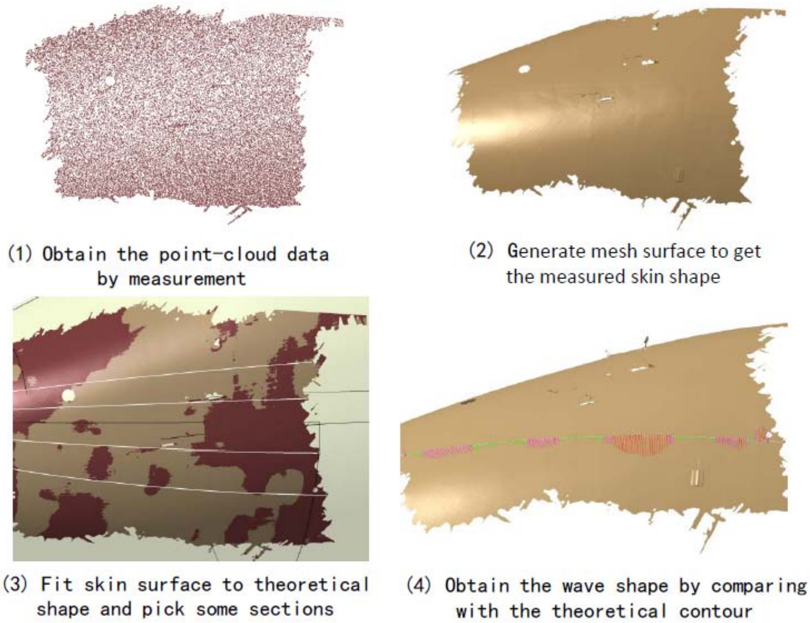

Figure 3 –Data sampling process.

The analysis of measured skin contour shows that there is a superposition of basic wave and local wavelet in the deviation between the actual skin contour and the theoretical contour[3]. The reason of local wavelet is rivets flushness, roughness or dirt on the surface, and so on. Therefore, it is necessary to filter out the wavelet and keep the basic wave only.

In order to filter the wavelet, multi-scale approximation is performed to the deviation signal of the measured skin contour relative to the theoretical contour. Firstly, the deviation $y(x)$ of the measured skin contour from the theoretical contour on the specified section is sampled, the original signal $y_J(t)$ composed of 2^J discrete points is obtained. Then, signal $y_J(t)$ is decomposed according to Mallat algorithm. Assume the number of decomposition layers is l, and $l < J$.

The decomposed signals of each layer can be expressed as:

$$\begin{aligned} y_J(t) &= y_{J-1}(t) + w_{J-1}(t) \\ y_{J-1}(t) &= y_{J-2}(t) + w_{J-2}(t) \\ &\vdots \\ y_{J-l+1}(t) &= y_{J-l}(t) + w_{J-l}(t) \end{aligned} \tag{1}$$

The approximate components of each decomposed layer are as follows:

$$y_j(t) = \sum_{k \in Z} c_{j,k} \varphi(2^j t - k) \tag{2}$$

And the detail components are as follows:

$$\begin{aligned} w_j(t) &= \sum_{k \in Z} d_{j,k} \psi(2^j t - k) \\ (j &= J, J-1, J-2, \cdots, J-l+1) \end{aligned} \tag{3}$$

Where $c_{j,k}$ is approximate coefficient, $d_{j,k}$ is detail coefficient, $\varphi(t)$ is scaling function, $\psi(t)$ is wavelet function.

The detail component of each layer reflects the local wavelet, the approximate component $y_{J-l}(t)$ of the l layer reflects the basic wave in the original signal, and the $y_{J-l}(t)$ is the filtered signal.

In this paper, sym6 wavelet is selected, which is an approximate and symmetric wavelet function proposed by Ingrid Daubechies. After the test, it is determined that the number of decomposition layers of sym6 wavelet should be 6 or 7.

The wavelet is filtered out from the original sample data to extract the basic wave, so as to extract the wave characteristic parameters. The original sample data and filtered data are connected into curves by spline, and the filtering effect can be seen by comparison, as shown in Figure 4

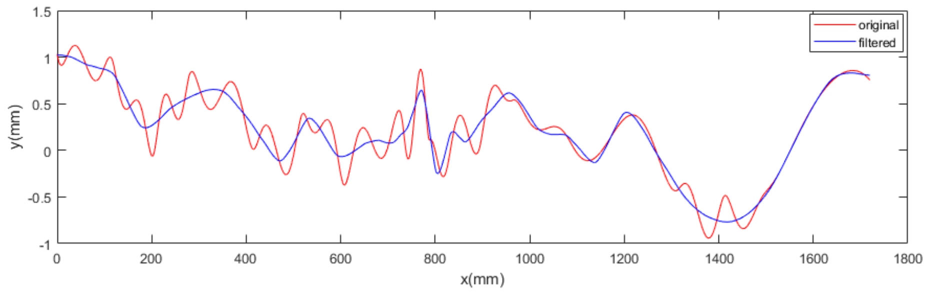

Figure 4 –The basic wave obtained by filtering the wavelet.

2.3 Characteristic Parameter Analysis

By extracting the wave characteristic parameters from the measured samples, the approximate wave length range of each component can be obtained, as shown in Table 1.

Table 1 –Wave length range of each component.

Component	Wave Length
Wing	100 mm - 800 mm
Fuselage	100 mm - 650 mm
Tail	80 mm - 450 mm

By analyzing the characteristic parameters, some phenomena are found:

- The wave length is generally less than or equal to the distance between the typical connection structures. Correspondingly, The wave length of the leading edge and the nose is relatively short, which is due to the small structural spacing;
- The wave height of leading edge and nose is smaller, while the wave height of trailing edge

and rear fuselage is larger. This is due to the difference of structural form and skin thickness, which proves that wave is mainly caused by structural connection stress;

- With the increase of aircraft size, the typical wave length increases correspondingly, but the increase is not obvious.

3. Calculation of Waviness

3.1 Calculation Criterion and Extended Application

According to the previous description, waviness is defined as h/λ. We only need to study the size of h to determine the waviness requirement, since the approximate range of wave length of civil aircraft is known. A waviness criterion is given by Carmichael, which is based on experimental results. Carmichael's criterion partially accounts for effects of compressibility, suction, pressure gradient, wing sweep, and multiple waves[4], so Carmichael's criterion in its general from is valid for 2-D or 3-D flow in form of single and multiple chordwise and spanwise waves on the wing surface. Carmichael's waviness criterion is given as:

$$\frac{h}{\lambda} = \left(\frac{59000 \cdot c \cdot \cos^2 \Lambda}{\lambda \cdot \mathrm{Re}^{1.5}} \right)^{0.5} \tag{4}$$

Where h is the wave height in inches, λ is the wave length in inches, c is the streamwise wing chord length in inches (mean aerodynamic chord length can be used when calculating), Λ is the wing leading-edge sweep angle and Re is the Reynolds number based on chord length and airspeed in the free-stream direction.

This formula can be converted to:

$$h = \left(\frac{59000\lambda \cdot c \cdot \cos^2 \Lambda}{\mathrm{Re}^{1.5}} \right)^{0.5} \tag{5}$$

It should be noted that this formula is suitable to the case of a single wave. For the case of multiple waves, the coefficient 59000 in the formula should be changed to 6600. Furthermore, the wind-tunnel and flight experimental results used to develop the coefficient actually varied over a range from 11000 to 38000 approximately. In the case of multiple waves, there is no accurate method to determine the coefficients in the formula, but Holmes et al. (1986) indicated that the results of Carmichael's criterion in single wave form are found to almost form an upper bound on the theoretical prediction results[5]. Therefore, we can use this formula for the single wave case to approximately calculate the required value of h and further obtain the requirement of waviness.

For fuselage, Carmichael did not give the calculation method of waviness. In this paper, the method of applying Carmichael's criterion to fuselage is given as an extended application of the criterion. Considering that the cylindrical fuselage of civil aircraft produce lift rarely, the requirement of waviness in non-sensitive area of fuselage is still calculated by Carmichael's criterion, but it is relatively conservative and can be relaxed in practical application. For the sensitive area of fuselage, such as the area near the pitot tube, c in the formula is the fuselage length, and the characteristic length used to calculate Re is also the fuselage length. The applicability of the extended application method of this criterion will be verified in the following.

3.2 Calculation of Civil Aircraft Waviness Requirement

According to Carmichael's criterion, h/λ is affected by c, Λ and Re. From the formula, it can be seen that: the larger c is, the lower the requirement is; the larger Λ and Re are, the higher the requirement is, and the influence of Re is more obvious.

For a particular aircraft, since c, Λ and Re have been determined, the relationship between h and λ can be obtained. For civil aircraft, 90 seats regional aircraft, 180 seats single aisle aircraft and 350 seats dual aisle aircraft are selected as the research models.

According to Carmichael's criterion, the relationships between λ and h for different seat class civil aircraft are obtained, as shown in Figure 5. It can be seen from the figure that the requirement of waviness is lower for regional aircraft and higher for dual aisle aircraft. With the increase of wave length, the increase of allowable wave height becomes slower, which indicates that the larger the wave length is, the higher the requirement of waviness is.

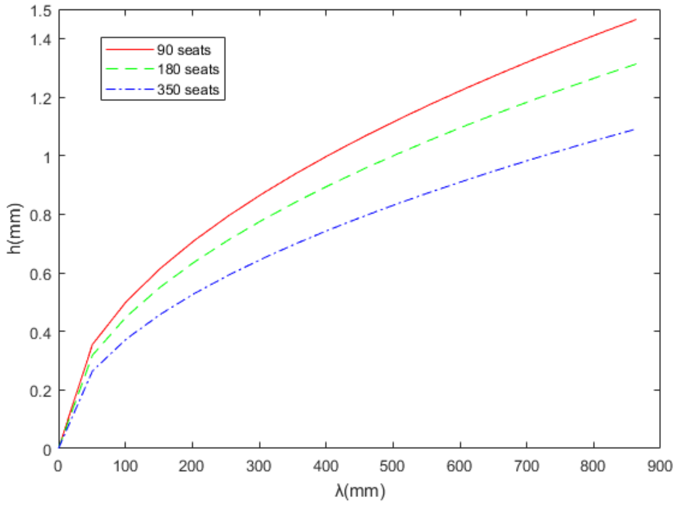

Figure 5 –The relationships between λ and h for different seat class civil aircraft.

According to Table 1, the wave length has a distribution range, so the maximum allowed value of waviness also has a value range. The range of maximum allowed values of waviness for different type of civil aircraft can be obtained from Figure 5, as shown in Table 2. In order to keep the natural laminar flow as much as possible, the waviness requirement should be considered based on this range.

Table 2 –The maximum allowed values of waviness for different type of civil aircraft.

Type of Aircraft	Maximum allowed values of waviness
90 seats regional aircraft	0.0018-0.0056
180 seats single aisle aircraft	0.0015-0.0050
350 seats dual aisle aircraft	0.0013-0.0042

3.3 The Method of Determining General and Special Waviness Requirements

Since the criterion is based on experimental results for waves located more than 25% chord downstream of leading edge, for waves located in very highly accelerated flows closer to the leading edge, the criterion may under-predict allowable waviness[6]. Conversely, the criterion would over-predict the allowable waviness in a region of unaccelerated flow. On the other hand, the wave length of leading edge and nose of fuselage are relatively short, while the wave length of trailing edge and rear of fuselage are relatively long. With the above factors considered, the relationships between λ and h will be more linear, as shown in figure 6, which means the range of waviness will be smaller and tend to be close to the middle value.

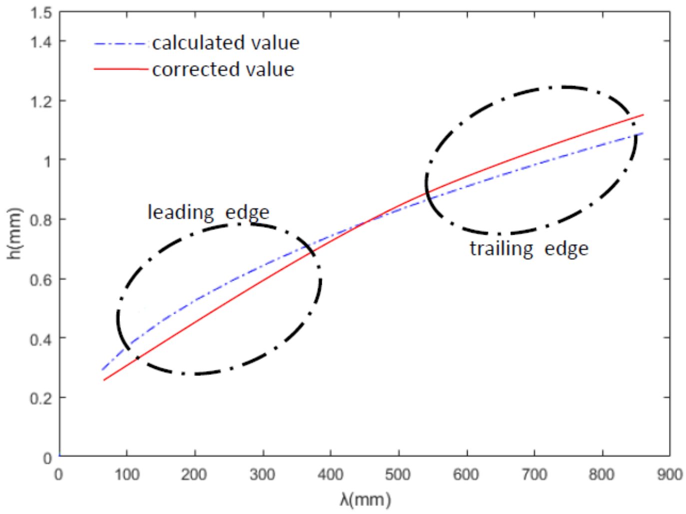

Figure 6 –The comparison of calculated value and corrected value.

Therefore, when determining the general requirement of waviness of a particular aircraft, it is feasible to take the middle value in the range of calculated waviness. When determining the waviness requirements of a specific area of an aircraft, the appropriate waviness requirements can be determined according to the position of the area and the characteristic structural spacing.

4. Validation of The Method

To validate the method, taking a typical aircraft as an example, the general and special requirements of waviness are calculated and compared with the actual requirements of the aircraft:

- For the general requirement of waviness, using the above method to calculate the waviness requirements of a 180 seats single aisle aircraft, the waviness range is 0.0015-0.0050, and the middle value is 0.00325. The calculated value is slightly larger than the actual waviness requirement value of this aircraft, and the error is less than 10%;
- For the special requirement of waviness, taking the area near pressure sensor as an example, the typical wave length near this area is 200mm. Based on the extended application method of Carmichael's criterion, c in the formula is changed into fuselage length and the value is 38m, Re number calculated by using fuselage length as characteristic length is $1.7*10^8$, and Λ is 0°. Through calculation, the waviness requirement of this sensitive area shall be 0.0020, which is almost consistent with the actual waviness requirement of the aircraft.

Therefore, Carmichael's criterion can be used to calculate the range of waviness and determine the general requirements of waviness. The extended application method of Carmichael's criterion can be used to determine the waviness requirements of the sensitive area of fuselage.

5. Conclusion

In this paper, the method of determining skin waviness requirement of civil aircraft is studied, the conclusions are as follows:

- According to the measured data of aircraft skin, the characteristics parameters of waviness are studied, and some distribution laws of the wave are found;
- Based on Carmichael's criterion, the relationships between wave length and wave height of different seat class civil aircraft are obtained, the ranges of waviness for different seat class civil aircraft are given, and the method of determining of general and special waviness requirements is proposed;
- By comparing the calculated results of waviness with the actual waviness requirements of a typical civil aircraft, it proves that the method of determining waviness requirement is valid. This method gives a reference for the formulation and improvement of waviness requirements of civil aircraft.

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