Research on the Variation Analysis Model for CFRP Assembly

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Abstract. The conventional error analysis model is based on Key Characteristics (KC) tree [1] and the nominal 3D assembly model. Before the actual execution of assembly process, the potential interferences and out-of-tolerance problems are simulated and predicted. Then the tolerance and assembly schemes of the parts are optimized accordingly. This method requires statistical deviation data of parts and it can only give a rough probability for mass production case. In this paper, the common CAT technologies, variation analysis and optimization method are presented with an example of wing box model in 3DCS. Based on KC tree and optimizing theories a model analysis method is proposed to improve the performance in the case of multi-material part assembly processes.

1. Introduction
A typical application process of CAT includes three main steps: identification of key characteristics [2], construction of deviation analysis models, and tolerance optimization.

1.1. Identification of key characteristics
The manufacturing process of aircraft involves various aspects of technology and applications which involves many different concepts at each stage. Therefore, how to accurately identify the corresponding KCs from these complex data becomes an important issue. The identification methods are mainly the following.

According to the assembly scheme: Under the premise of a complete assembly scheme, characteristics which are used in locating and connection by parts are found out as the KCs. It normally starts from the lowest part level until the highest product KCs are found. Each step in the process also include analysis of the direction and route of error transmission to optimize the assembly scheme.

Reasoning based on statistical data: Starting from the error statistics in the manufacturing process, combined with the process requirements and assembly schemes, the source of error is reversed and the key characteristics are derived.

The risk analysis method: This method is based on the formula to determine the risk priority number (RPN) of the characteristics to be selected:

\[ RPN = S \times O \times D \] (1)
In formula (1), \( S \) (Severity) is a subjective value used to measure the severity of the failure. \( O \) (Occurrence) represents the possibility of failure when using which is also a subjective value. \( D \) (Detection) represents the degree of difficulty in detecting potential failures before the product is completed. These three numerical evaluations range from 1 to 10. After evaluating all candidate, the high-risk characteristics will be chosen as KCs.

The historical data analysis method: This method is based on the statistical data of scrapped parts generated by the workshop and the analysis results of causes to obtain the KCs. With all data generated in the actual production process, its subjective factors are relatively low, and the results are reliable.

1.2. Establishing an deviation analysis model
The purpose is to simplify the complex error behaviour and to optimize the part tolerance with the model. Researchers have proposed various models, such as the classics dimension chain model, analytical models based on deterministic locating, etc.

The dimension chain model: it is actually a highly simplified theoretical model because the amount of information that can be carried by each link is very small. In the process of extracting the dimension chain, most of the geometry characteristics of the part are neglected, so it is suitable for a simple structure. For complex one, the extraction process and calculation will be complicated. The result will also be too theoretical. In addition, for products that use a large number of fixtures in the assembly process, the dimension chain model also has limitations in analysing the introduction of fixtures’ errors.

Analytical model based on deterministic locating: Compared with the dimension chain model, this model is closer to the actual assembly process. It can introduce the errors of the fixture well. The complex assembly can also be analysed and solved. However, because of its computational complexity [3], to solve this model relies more on computer programs. Sometimes the quality of the algorithm can even determine the analysis speed and the accuracy of the results. Facing the large-scale structures, the complexity of its locating will spend a lot of staff energy and time to complete the set-up process. The analysis and calculation process also has relatively high requirements for the hardware.

1.3. Tolerance optimization
In fact, the difficulty of optimization process depends on many front-end factors. For example, a reasonable assembly scheme can allow a large room for tolerance optimization without having to compress the tolerance zone of some parts to very narrow, because the errors can be maximally eliminated during the assembly process. An excellent part design can also significantly reduce the sensitivity of the error transfer to the part geometry, thereby saving the cost of modifying the part shape and assembly method.

Generally iterative method is used to optimize tolerances. That is, starting from a presupposed set of tolerances, after the operation of repeated analysis and improvement, the set of tolerances will be approximated to the optimal solution.

2. Wing box assembly process and error analysis
“In the aircraft manufacturing process, the shape accuracy requirements are much higher than the assembly accuracy requirements” [4]. The appearance characteristics of aircraft are usually given priority, and the accumulated errors are eliminated through the connections of inner structure. Therefore, the assembly process also affects the transfer and cumulation of errors.

The actual assembly process can be expressed by formula (2) and Figure 1 shows the main structure of the wing box:

\[
P = \{\text{step1, step2, step3, step4}\}
\]

\( P \)—process (wing box assembly).
Step 1: locating and assembly of the leading edge-front spar component [5].
Step 2: locating and assembly of the trailing edge-rear spar component.
Step 3: locating and assembly of the ribs.
Step 4: locating and assembly of the panels.

**Figure 1.** Structure of wing box assembly

**Figure 2.** Transfer of KCs’ own fluctuations

**Figure 3.** Introduction and delivery of locating errors

With analysing the detailed assembly process, a global error transfer routes can be drawn as Figure 2 which shows all parts, assemblies and KCs that appear in the process and how their deviations will
transfer and accumulate. Besides, Figure 3 shows the introduction and delivery of locating errors. In the two figures: LH—Locating Hole. LS—Locating Surface. MS—Mating Surface. AS—Aerodynamic Surface. JH—Jig Hole. SS—Side Surface. SawS—Saw tooth Surface (they form the seam in upper panel).

3. Tolerance allocation technology based on 3DCS
Based on the detailed deconstruction and analysis in Chapter 2, this chapter will show the analysis result of the gap between metal wing ribs and panel made of composite material. To run the analysis in 3DCS, parts’ preset tolerances, Move (assembly scheme), and Measure scheme are indispensable. Table 1 shows the original tolerance scheme of upper panel.

| KCs     | Position | Size range | Range | Offset |
|---------|----------|------------|-------|--------|
| LH 1    | Φ0.1    | 0.04       |       |        |
| LH 2    | Φ0.1    | 0.04       |       |        |
| LH 3    | Φ0.1    | 0.04       |       |        |
| SawS    |         | 0.3        | 0     |        |
| UAS     |         | 0.2        | 0     |        |
| 4-5InnerS |       | 0.223      | 0     |        |
| 5-6InnerS |       | 0.270      | 0     |        |
| 6-7InnerS |       | 0.316      | 0     |        |
| 7-8InnerS |       | 0.366      | 0     |        |

Due to design requirements, the skin is not uniform but gradually thickens from 4mm to 8mm. So the measurement points should be set in different thickness regions. For the connect position, a small size of gap is normally more acceptable than interference which causes the deformation of product shape. Figure 4 shows the results of conventional method which uses random variation to build the analysis model in four regions.

(a)         (b)
Figure 4. Analysis results of gap in four different regions with original tolerance

The fluctuation range of the gap are: 0.38mm of 4-5mm region, 0.42mm of 5-6mm region, 0.44mm of 6-7mm region, 0.44mm of 7-8mm region, gradually growing larger with the skin thickening. This is because the deviation of skin is calculated at 5% of its nominal thickness, so the skin itself fluctuates more in thicker regions. In the figure, the unqualified ratio is all about 50%. Although the skin itself is the largest source of fluctuations, modifying the tolerance of the composite material skin is still not suitable, so the target turns to the aerodynamic surface of rib. After adjusting the tolerance zone of it inward by 0.1 mm, the new result is shown in Figure 5.

Figure 5. Analysis results after optimization
The unqualified rate is respectively reduced to 5.4%, 7.35%, 7.95%, and 10.9%. The optimization effect is very obvious.

4. Variation analysis of multi-material parts assembly

The idea of multi-material assembly is to apply composite material to the secondary parts of the structure, but in important supporting frames, bearing structures and parts with high precision requirements. The machined metal parts are still used. Assembly made up of parts with different properties has brought a lot of problems to the assembly work.

Here proposes a new idea to improve the analysis method of the multi-materials assembly. The preset tolerance of the composite part was abandoned in the original analysis process. Set its true deviation directly. The goal is to transfer the error as much as possible to metal parts that can be optimized to a narrower tolerance zone. Figure 6 shows the difference between the new method and conventional one in error accumulation.

![Figure 6. Full metal assembly and multi-materials assembly](image)

For composite parts A with large deviations, the tolerance band is T and the deviation is \( \Delta A \).

\[
\begin{align*}
\Delta A & \in (\min, \max) = T \\
\quad P(\Delta A = \max) = 0 \\
\quad |\max - \Delta A| = C & \neq 0
\end{align*}
\]

Formula (3) shows that after the deviation of A is set, there is a tiny blank space C between the deviation value and the original tolerance zone, and this interval will be allocated and merged into other parts that cooperate with A.

\[
\begin{align*}
A & = C \times \text{Con(partA)} \\
B & = C \times \text{Con(partB)} \\
\ldots
\end{align*}
\]

Formula (4) shows that the allocation of the blank interval C is performed according to the contribution rate of other parts, and the assigned amount is added to the tolerance band of the corresponding part.

The new method is applied at the four representative measure points by adding the measured deviation value. To input the deviation data into the model, the data structure of compiled DEV file is adopted to bring deviation information into the 3DCS system. The actual measured corresponding deviation values are shown in Table 2.

| Area of skin | Variations/mm |
|--------------|---------------|
| 4-5mm        | +0.048        |
| 5-6mm        | -0.057        |
| 6-7mm        | +0.012        |
| 7-8mm        | -0.047        |
The corresponding aerodynamic surface of the wing ribs is still set to a tolerance of 0.2mm as the conventional method and a normal distribution is used to randomly select the deviation value. The Move and the four measurement points are the same as it in chapter 3. The new results are shown in Figure 7.

![Image](image1.png)

Figure 7. Analysis result of new method with actual variation involved

The analysis results show fluctuation range of this method: 0.25mm of 4-5mm region, 0.24mm of 5-6mm region, 0.24mm of 6-7mm region and 0.24mm of 7-8mm region. The range values of the four regions are very similar. At the same time, all the most contributing factors are the fluctuations of aerodynamic surfaces of the rib which are all above 60%. This shows that after the panel deviation is set to an actual constant value, its fluctuation is ignored and the critical analysis object is transferred to the rib. This is exactly what we expect.

In terms of the unqualified rate, the directions of deviation of the skin in the four areas are different. The out-of-tolerance regions also shows different proportions, and targeted analysis must also be carried out in formulating optimization plans.

In the 4-5mm area, due to the deflection of the skin towards the ribs, the wing ribs should be reduced in size accordingly, reducing its size by 0.15mm and the aerodynamic surface tolerance zone by 0.1mm.

In the 5-6mm area, since the skin deviates away from the ribs, it only need to reversely offset the aerodynamic surface tolerance zone by 0.05mm.

In the 6-7mm area, the skin shift is small and close to the nominal position, and the tolerance offset value should be larger to avoid interference, set the offset by 0.1mm.

The 7-8mm zone is similar to the 5-6mm zone. The skin deviates away from the ribs. It only needs to offset the tolerance zone of aerodynamic surface by 0.07mm.
According to the above optimization plan, the values used in analysis are optimized. Run the calculation and statistics again and the new results of the width of gap between skin and rib are as follows.

![Figure 8](image)

**Figure 8.** Analysis result of new method after applying optimization

As shown in Figure 8, when using the optimized scheme, the unqualified rate at each measurement point is greatly improved and they are all less than 2%. In the example, by adding the actual measured deviation to the model, the error factors are concentrated on the rib that matches the skin. In order to eliminate these comprehensive errors, different targeted optimization schemes are also formed in regions with different deviations. The resulting tolerance scheme of the ribs can actually guide the corresponding characteristics in the manufacturing process to ensure that the machined ribs can be perfectly coordinated and matched with the specific skin during assembly. In the process of new product development and prototype assembly, this tolerance analysis method based on concessions for composite parts is more targeted and instructive than the conventional method of adding random deviations.

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