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Aircraft Assembly Quality Control With Feedback Actions and Assembly Station Flowing Fluctuation Analysis

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ABSTRACT For complex products, as the size, shape, position and other properties of the geometric features changing, the accumulated assembly error or the coordination error between different assemblies would be affected directly. How to keep these key geometric characteristics in a statistical state, especially in the process of batch production, is an important factor to ensure error consistency. Aiming to control the assembly quality, optimization methods for key characteristics of aircraft products with feedback actions and ASFF (Assembly Station Flowing Fluctuation) analysis is proposed. Firstly, by collecting and constructing statistical quality samples, based on SPC (Statistical Process Control) method, criteria on abnormal assembly quality was analyzed, with qualitative practical experience. Secondly, four specific assembly controlling actions with a feedback loop were adopted by quantitative analysis, including PCF (Product Coordination Feature) identification, PCE (Process Coordination Element) mapping, CR (Coordination Relationship) modelling, and assembly error propagation modelling. Thirdly, the concept of ASFF was proposed, and the trajectory chart was plotted to evaluate the deviation and fluctuation of assembly error under one assembly station. This analysis was done by calculating the process offset and stability, according to the dynamic change of assembly quality status data at different time stages. Finally, with the specific improvement actions, i.e. (1) diagnosing the abnormal sources and improving the assembly operating process, (2) analyzing the dynamic deviation and fluctuation of assembly quality data within a specified assembly station, and (3) improving the assembly assurance ability, the out-of-tolerance problem of the skin profile was optimized to verify methodology's feasibility. Benefit results are gained, i.e. the locating state of ending ribs was more accurate, and the assembly process became more stable. With the rapid growth of aircraft production, the quality controlling method would be much helpful especially in the batch manufacturing stage.

INDEX TERMS Quality controlling, aircraft assembly, feedback actions, flowing fluctuation analysis, skin profile.

I. INTRODUCTION

With the appearance of the concept of Key Characteristic (KC), lots of research work has been done in aircraft manufacturing field with the view of KC's identification and controlling [1]. Correspondingly, the quality of aircraft assembly has a substantial improvement. However, as the size, shape, position and other properties of the geometric features distributing on aircraft products changing, the accumulated assembly error and the coordination error between different assemblies will be affected directly [2]. Where the coordination error is defined as the consistency between different assembly error items, both in error accumulation direction and numerical value. How to keep these key geometric

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characteristics in the statistical state, is an important factor to ensure the error consistency and the manufacturing efficiency [3].

In order to control the assembly quality for key characteristics of aircraft products, the traditional analysis work on the change of key geometric characteristics mostly relies on personal manufacturing experience and the company's regulations on quality management. Then the standardized non-conformity procedures ensure that deviations are mitigated and then accepted. However, as handling the quality problems, these specified knowledge in aircraft manufacturing requires high skills for engineering technicians, and the judging repeatability with different workers is also not stable. Correspondingly, this work is mainly dependent on people, and the effectiveness could also be improved. With the purpose of enhancing the manufacturing accuracy and quality, in 1994, the SPC principle was introduced into the aircraft assembly process by Boeing aircraft manufacturing company [4], [5], as shown in Figure 1. Based on the PLM (Product Lifecycle Management) software *(www.eds.com)* [6], [7] and the virtual assembly technology [8], [9], with the help of SPC technology for KC, the rework rate and design changes of Boeing 777 and JSF (Joint Strike Fighter) X-32 were reduced by more than 50% [10], [11], and the quality problems occurring in the assembly process were reduced by 50%∼80% [12]. Taking the strategies of reducing the variation in the whole manufacturing process, and controlling the key characteristic with the above SPC method into account, the manufacturing/assembly quality can be improved for the aircraft manufacturing. With regard to the quality controlling methods, the SPC chart is used to monitor and analyze the fluctuation for the samples of key error factors in the assembly/manufacturing process. As the phenomenon that assembly quality samples go beyond the control range coming up, the fluctuation source should be determined and identified immediately and efficiently, and then relevant solutions should be taken for the sake of keeping them in the statistical control state.

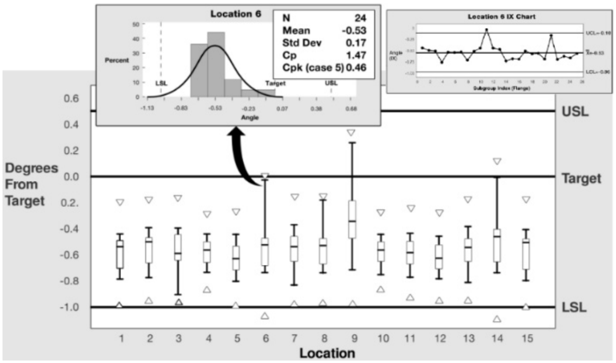

FIGURE 1. **The SPC system of Boeing company (for upper flange angle, 24 parts contained).**

For the SPC method, much research work has been done. MacGregor and Kourti [1] pointed out that the SPC method was not only fitting for the quality data of products, but also aiming at controlling all the variables of the whole manufacturing process. Tsung *et al.* [13] proposed a special SPC method that relating with multistage processes based on SSM (State Space Model). Then in order to design the multivariate control scheme effectively, Epprecht *et al.* [14] proposed genetic algorithms for optimizing the charts parameters. Halevi [15] described that quality controlling was a process that management seeking to ensure, with which the product quality was maintained or improved and manufacturing errors were reduced or eliminated. And a conclusion was gained, i.e. SPC was a technique for error prevention rather than error detection. With the purpose of minimizing the expected cost per unit of time in manufacturing process, Jonathan *et al.* [16] proposed a mathematical controlling model, and the final quality was limited to the desired level. When smaller parts were welded together to a complete jet engine, key product characteristics, such as geometrical variation and weld quality always difficult to fulfill. With quality management solutions, such as drawing the cause and effect diagrams, variables interrelationship matrix, Ola [17] analyzed how parameters affect weld geometry in order to work more systematically when putting efforts in how to improve their fabrication processes. For other research areas, taking the discrete manufacturing process for example, such as automobile and ship manufacturing, Fang *et al.* [18] built a quality controlling system based on SPC, and the system was suitable for the production process quality analysis and judgment. Aiming at improving the assembly quality, Li *et al.* [19] proposed a method relating with error source tracing, where the SPC method was used to judge the abnormality by the distribution and trend of positioning errors. In detailed, based on the measurement data from laser trackers, shape data of aircraft components was accumulated, and then the small assembly data was estimated with supervised learning method to trace error source rapidly. For all finished products, in order to determine the need of any change in specification or manufacturing, Kharbach *et al.* [20] believed that they should be reviewed annually by referencing the quality standards, and SPC was an efficient method to overcome this issue. Then according to the following situation, i.e. only a few statistical process monitoring or SPC approaches for controlling quality in high dimensional multistage processes were studied, Sangahn [21] proposed a MEWMA (Multivariate Exponentially Weighted Moving Average) control chart based residual deviance, with a variable selection procedure to solve the problems mentioned above. Hoon *et al.* [22] indicated that there still exist the limitations of manual data collecting and experience analysis, and the solution of intelligent software might be helpful, although the advantages of SPC in manufacturing industry had been gained.

With the review work that mentioned above, an obvious conclusion can be gained, i.e. the SPC is the conventional method can be used in manufacturing quality controlling and improvement. However, for aircraft manufacturing, there is a specific characteristic of "three multi- and two high-'' for the detailed assembly process, i.e. multi-assembly station, multi-product hierarchy, multi-datum transformation, high-assembly accuracy, and high-consistency requirements among different assemblies. And there are difficulties for the practical application of SPC method. For the supplier, with regard to the subcontract production for the plane project of B737/B787 in Boeing company and A350 XWB in Airbus company, by virtue of (1) the identification of KCs, (2) statistical data sampling, (3) SPC chart graphing, and (4) abnormal cause analysis, the quality controlling actions were carried out in Harbin Hafei Company [23], and India institute of technology [24]. Combined SPC with an unsupervised learning method, i.e. SOFM (Self-Organization Feature Mapping), Li *et al.* [19] proposed an error source tracing method aiming at improving the assembly quality. With non-ideal sheet-metal parts, Beruvides *et al.* [25] proposed a reinforcement learning-based architecture to address the fault detection on body in assembly processes. Although the monitoring and analysis work have been done for assembly quality controlling, the current SPC method cannot provide the detailed controlling solutions that fitting for the specified assembly and manufacturing operations or process, and the detection of the weak error links and the benefit advice fitting for the problems cannot be solved.

From another perspective, for most of the SPC techniques, they mainly focus on the assembly quality of the KCs itself. Whether the results of multiple quality samples are in the stable and controlled state, is reflected. However, given these quality data samples locating in the required threshold, only whether their deviations exceed a pre-defined threshold is concerned currently, not on their fluctuation status or variation trends within the limits of the threshold at different time stages. It is noteworthy that these quality data is also not independent with each other, because they may originate from the same assembly fixture, assembly procedure, or assembly time stage, etc. And this interrelation relationship is often ignored. Actually, the quality state of each assembly station varies dynamically over time in the assembly process. The main sources for this phenomenon are assembly environment, manufacturing error of parts, assembly loads or force during assembly procedure, positioning accuracy of digital assembly tooling, measurement error, etc.. Therefore, the well-known SPC methods lacks the capability to distinguish the changes of different assembly stages. Aimed at this situation, Ertugrul and Aytac [26] constructed two quality control charts by using probability and fuzzy approaches respectively. To ensure the processes stability of MMPs (Multistage Machining Processes), and improve the quality of machining process, a real-time quality-monitoring model based on PVTC (Process Variation Trajectory Chart) was proposed for monitoring the key machining stages [27], [28]. Then the machining error propagation for a box part of a missile launcher and the machining process of a connecting rod were verified. However, the focus of the above work is not appropriate for the dynamic change of the given assembly situations and stations, and the deviation/fluctuation of assembly results cannot be reflected, i.e. the data samples under one certain assembly station, and at different time phases. Paying attention to the deviation/fluctuation that formed under a certain assembly station, can improve the ability of guaranteeing the product assembly quality. With the rapid growth of aircraft production, the above problems would be more serious, especially in the process of batch stage.

In this paper, in order to (1) further analyze the fault source and improve the assembly process operations, (2) pay attention to the dynamic deviation and fluctuation of assembly results within a specified assembly station, (3) improve the assurance ability on assembly quality, the assembly quality controlling method for key characteristics of aircraft products is proposed, i.e. the method with five feedback actions and ASFF analysis. The remaining sections of this paper are organized as follows. In Section II, the product key features in aircraft assembly with SPC method is analyzed, based on qualitative practical experience. With quantitative modelling analysis, Section III presents four specific assembly controlling actions. At different time stages, Section IV shows the detailed process for assembly station flowing fluctuation. In Section V, the key assembly characteristics of the four wing flap component are taken as the verification object. Conclusions are drawn in the final Section VI.

II. SPC FOR PRODUCT KEY FEATURES IN AIRCRAFT ASSEMBLY

A. OVERALL FRAMEWORK FOR SPC TECHNOLOGY

For aircraft assembly, the SPC technology that used for product key features originates from the Advanced Quality System (AQS) in Boeing Company. Its essence is to control the final assembly quality of the product in the manufacturing process. With this method, benefit results can be gained, i.e. (1) the fluctuation of the product key characteristic can be reduced to a lower level, (2) the statistical control state of the above characteristics can be kept, (3) the occurrence of assembly error inconsistency can be minimized. For SPC, with monitoring and analyzing the fluctuation of quality samples that collected during assembly process, when the acquired actual value goes beyond the control range, it is necessary to find out the detailed cause of assembly problems efficiently, such as the assembly precision or assembly stress cannot meet the design requirements. Where the assembly stress is defined as the internal residual stresses in the final assembled structure, which is caused by manufacturing errors of parts, positioning error of assembly jig, clamping/drilling/jointing forces during assembly process, etc.. Then relevant solutions would be determined, and with the adjustment on the specified manufacturing process, the purpose of assembly quality controlling can be achieved.

B. ANALYSIS ON SPC CHART IN AIRCRAFT ASSEMBLY WITH QUALITATIVE PRACTICAL EXPERIENCE

As well known, the manufacturing/assembly for aircraft has the characteristic of medium and small scale production.

When the production process is in a stable state, for the measuring and detecting accuracy data of quality samples, they are considered obeying the normal statistical distribution in most cases. It is assumed that for the two corresponding important parameters, i.e. the mean value and the standard deviation, they are independent with each other based on the statistical analysis of a large number of samples. However, with regard to the collected data of several measuring points for given aircraft components, they belong to the category of small samples in practical production statistics. For aviation products, even in the batch production phase, the sample size could not be particularly large. This would cause an insufficient information. Then the distribution principle and the statistical parameters of the random variables are always unknown. As a result, the calculations that fitting for probability distribution orienting for large sample data, such as parametric estimation, hypothesis testing, and regression analysis, also cannot be applied to the small samples analysis well. As a result, there is not enough data information to judge the assembly precision accurately, which would lead a difficulty to the SPC analysis process.

For the purpose of expanding the statistical information of the measurement data maximally, and revealing the potential error accumulation principles, the construction process of the quality sample size is analyzed firstly. In the aircraft assembly process, the measurement characteristics, such as the measuring points corresponding to the final assembly error links, are usually distributing symmetrical for aircraft components. And with regard to the similar type of the detection geometric features, or the similar assembly cases, if the manufacturing specifications or conditions, for instance (1) assembly quality requirements (such as the deviation of skin profile), (2) skills of workers and technicians, (3) process equipment/tooling, (4) measurement means, and (5) external conditions (such as the environment factor, etc.) are basically the same as each other, then these characteristics can be considered as having the same fluctuation situation. Correspondingly, the above characteristics obey the same normal distribution, i.e. the values of statistical mean ($\overline{X} = \left(\sum_{i=1}^{n} X_i\right)/n$) and standard deviation ($S = \left[\sum_{i=1}^{n}\left(X_i-\overline{X}\right)^2/\left(n-1\right)\right]^{1/2}$) are equal with each other.

With the above analysis, for the sake of solving the situation of insufficient data sample size, the data of these detection points can be combined together to construct a relatively larger amount of data samples, and it is helpful. It is noteworthy that only product quality data is combined here. At the same time, the standard transformation method can be utilized to transform the data that having a distribution of $N(0,1)$ from $N(\mu_i, \sigma_i)$. And then the specific relevant analysis can be carried out in the statistical control chart. The chart adopts the conventional W. Shewhart control chart for quality control [29], and it is composed of central line (CL), upper control line (UCL) and lower control line (LCL), as shown in Figure 2. Where the x axis stands for the data samples, and the y axis represents the value of their quality characteristic. It is notable that the UCL and LCL are determined by the customer's or the assembly requirements, which cannot be changed randomly as the manufacturing process flowing down. And the range of UCL/LCL is often tighter than the tolerances demanded from customers or from design/manufacturing/assembly.

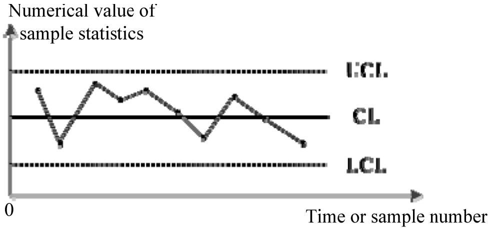

FIGURE 2. The SPC chart.

According to the detection value of key product elements in a specified manufacturing link or error link, the individual moving range chart, i.e., is used for statistical controlling in aircraft assembly process. X stands for the detection value of each quality sample. The moving range R_S refers to the difference value between different adjacent data items, and the sample number is 1. To the aircraft assembly process or operations, the construction principle of $X - R_S$ can be described as follows.

Step 1: Collect the quality sample data for m components. For example, the positioning error of the tooling, the manufacturing precision of the comprised parts, the assembly accuracy or the coordination accuracy of the key assembly features. It is notable that these data is the foundation for SPC analysis.

Step 2: For each component, n sample measurement points are contained, and the values are denoted as: $x_{11}, x_{12}, \cdots, x_{1n}, \cdots, x_{i1}, x_{i2}, \cdots, x_{in}, \cdots, x_{m1}, x_{m2}, \cdots, x_{mn}$.

Step 3: Assuming the manufacturing and assembly process is in a stable status, which means each value has a normal distribution of $x_{ij} \sim N\left(\mu, \sigma^2\right)$, then for a certain component, the moving range R_s can be calculated by (1).

$$R_{sij} = \left|x_{ij} - x_{i(j-1)}\right| \tag{1}$$

And the average R_s can be calculated as:

$$\overline{R_S} = \frac{1}{m\left(n-1\right)} \sum_{i=1}^{m} \sum_{j=2}^{n} R_{sij} \tag{2}$$

Step 4: For the individual control chart of quality sample [28], there is:

$$\begin{cases} UCL = \overline{x_{ij}} + 3\sigma = \overline{x_{ij}} + 2.66\overline{R_s} \\ CL = \overline{x_{ij}} \\ LCL = \overline{x_{ij}} - 3\sigma = \overline{x_{ij}} - 2.66\overline{R_s} \end{cases} \tag{3}$$

where σ is the overall standard deviation of the data samples, and it has a specific relationship with C.

For the moving range R_S control chart of quality sample [17], there is:

$$\begin{cases} UCL_{R_S} = \overline{R_S} + 3\sigma_{R_S} = 3.27\overline{R_s} \\ CL_{R_S} = \overline{R_s} \\ LCL_{R_S} = \overline{R_S} - 3\sigma_{R_S} = 0 \end{cases} \tag{4}$$

where σ_{R_s} represents the standard deviation of R_S. The result of LCL_{R_s} generally is less than 0, considering the definition of R_S, this result can be taken as 0, for the convenient analyses on the SPC datagraphic.

With the view of influencing factors and statistical analysis, some intuitive conclusions can be drawn on assembly quality controlling for the manufacturing system quickly, with the help of estimating the mean value and the standard deviation with the $X - R_S$ chart. If the measured sample points that described in the control chart exceed the control limit, it is considered that the statistical process is abnormal, and there are problems in the manufacturing process that leading to the phenomenon of out of bounds. With the analysis on the above chart, it is necessary to analyze the distribution status or trends of sample data in SPC chart. Actually, there are two main types of abnormal phenomenon, i.e. the sample measurement points are beyond the limits, and the sample points are not arranged randomly within the boundary. On the basis of a large amounts of practice working, the criteria for judging the rules of SPC control chart have been summarized, and they have a mapping relationship.

According to the actual measured characteristics of aircraft assembly coordination process, and the common problems occurred for the inconsistency of different assembly errors, the specific rules for distinguishing the causes of the abnormal fluctuation that leading to the assembly accuracy problems, can be summarized as below. And the following criteria is mainly based on engineering experience and the company's regulations on quality management.

(1) When the position of some measurement points is just locating at the upper and lower control line, or locating beyond the upper and lower control lines, it can be judged that there is a significant system error in the manufacturing and assembly process. Most of the time, the above phenomenon is caused by the error of measurement system, the significant change of assembly environment, the instability in automatic controls of FAT (Flexible Assembly Tooling), the obvious shortcomings of assembly scheme, the erratic holding fixture, the incomplete operation, and so on. It is notable that for the assembly scheme, the locating method and the tolerance distribution program are mainly included. The above inapposite settings should be corrected immediately. However, the over adjustment might also cause the phenomenon, and it needs a theoretical guidance.

(2) When the measuring sample points fall outside the section $[\mu - 2\sigma, \mu + 2\sigma]$ frequently, the phenomenon indicates that the standard deviation has an obvious large parameter value. And it can be considered that the manufacturing and assembly process is abnormal. The common causes can be thought as following: the equipment/tools are not working properly in the assembly process, or the locating and clamping accuracy of the end locators cannot fit the design requirements, or KCs with a very loose engineering tolerance, or the distribution of required upper/lower tolerance limits should be relocated. With the purpose of solving the above problems, the positioning and clamping state of the tooling or equipment should be checked and recalibrated to meet the assembly requirements.

(3) When the quality characteristic points distribute on both sides of the center line, however, the modes of step rise and step drop appear. This abnormity indicating that there is a change for the mean value of the statistical results, and there is a type of systematic error that causing the shifting. Although the steps in $X - R_S$ may indicate the assembly process was intentionally changed or improved, we analyze the distribution of quality data before benefit solutions are taken. As a result, the conclusion is summarized that the systematic error is mainly contained by the change of physical environment, such as temperature/gravity, or the operator skill level, or the drilling/jointing deformation.

(4) In the statistical control chart, when the distribution of the measurement points showing a noticeable continuous upward or downward trend, it can be considered that the manufacturing and assembly process is affected by a continuous change of the external factors. For example, the wear of assembly tooling, something loosening happened in assembly fixture, and inappropriate sampling frequency, etc.. The above factors would lead to the reduction of the quality in the manufacturing/assembly process. Process solutions that having the opposite effect should be taken, for amending the samples locating besides the central line.

(5) For one kind component of different sorties, when plenty of the measurement points having the trend of increasing or decreasing at the same time, and demonstrating the same fluctuation status in the manufacturing/assembly process, then this situation indicates that the assembly quality is affected by a certain system error at one certain direction. The reasons maybe, for example, operator, measurement system, assembly procedure, locating/jointing devices, and so on.

(6) During the assembly process among different sorties, when the measurement values of the same characteristic/feature having a relatively fixed relationship with each other, it can be regarded that there is a deterministic system error occurred in the manufacturing process. Under this condition, the most important reason may be the inherent positioning deviation state of assembly tooling/fixture, and it‘s necessary to re-calibrate the equipment for satisfying design requirements before starting the detailed assembly work.

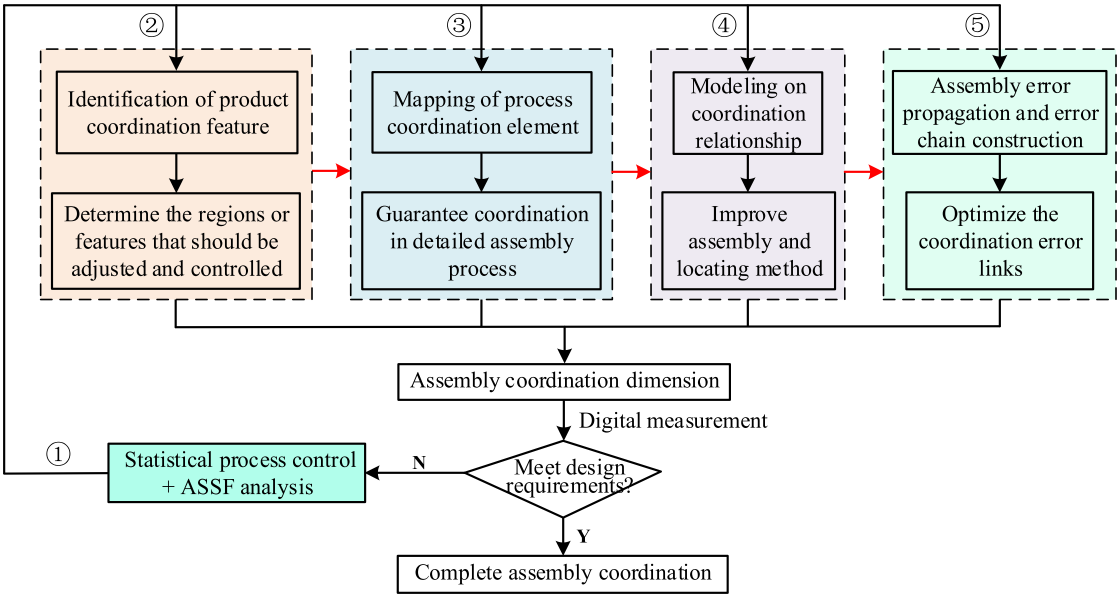

FIGURE 3. **Control flow for controlling assembly coordination dimensions.**

By applying the above empirical criteria and solutions with a qualitative manner, i.e. the company's regulations on quality management rather than the theoretical calculation, it is easy to judge the abnormal reasons that existing in the detailed manufacturing/assembly process of aircraft products. Then relevant adjusting strategies and improvement solutions can be put forward to optimize the assembly process.

III. ASSEMBLY FEEDBACK CONTROLLING ACTIONS WITH QUANTITATIVE MODELING ANALYSIS

The six criteria mentioned in the above chapter can help the technicians discover the manufacturing principles, and predict the new abnormal quality points in the forthcoming assembly step or station. However, these criteria are mainly based on the workers' practical experience, not on the mathematical modeling. And it is a qualitative analysis method in essence. When an assembly problem generates, specific controlling solutions should be taken, for the purpose of keeping the *KCs* in a stable status, and controlling the assembly coordination accuracy to meet the design requirements. Unlike the empirical analysis or the qualitative analysis based on the previous *SPC* chart, the detailed strategies based on quantitative analysis can be shown with Figure 3. Where the function process are expressed by the solid arrows. For the relationship of four specific assembly controlling actions, i.e. from the 2$^{\text{nd}}$ to the 5$^{\text{th}}$, they both have a cause/effect and paralleled relationship. Firstly, the four optimization steps can be carried out in parallel. And it is notable that the optimization results from the previous step, can also be taken as the input for the next step. These four steps, i.e. *PCF* (Product Coordination Feature) identification, *PCE* (Process Coordination Element) mapping, *CR* (Coordination Relationship) modelling, and assembly error propagation modelling, would form an organic whole, for the ultimate goal of guaranteeing the assembly quality. Their strict logical relationship can be expressed as following. Section III.A determines which geometric feature of the product is critical, or the regions needing to be paid a close attention and adjustment. Section III.B answers which process element affecting assembly/coordination accuracy of the product. The *PCE* has a close mapping relationship with *PCF*, and it affects assembly/coordination accuracy of *PCF*. Section III.C describes the geometric constraint relationship or the precision relationship between the *PCF* and *PCE*, and the constraint result is taken as an error link for the entire assembly process. Section III.D explains the modeling of different kinds of error items, with the analysis on their coupling/accumulation relationship, and the final assembly error chain can be gained.

A. IDENTIFICATION OF THE PCF

Based on the comprised parts and components of the aircraft's products, some critical assembly/coordination regions or features that needed a close attention and adjustment should be defined firstly. Such as locating/joint interfaces, mating surface, or the breakdown interfaces for designing and manufacturing, etc. These identified product *CFs* can be considered as the objects needing a feedback controlling, when they cannot meet the assembly/consistency requirements.

According to Taguchi quality loss function [30], when the variation of potential alternative PCF (donated as c_i) deviating from its target value, a quality loss would occur, i.e.

$$L = k\left((\mu - m)^2 + \sigma^2\right) = k\left(\delta^2 + \sigma^2\right) \tag{5}$$

$$k = \frac{A}{\left(\frac{TU-TL}{2}\right)^2} = \frac{1}{\left(\frac{TU-TL}{2}\right)^2} = \frac{4}{[TU - TL]^2} \tag{6}$$

where L represents the quality loss of c_i; k represents the quality loss constant of c_i; δ indicates the quality offset as the mean value μ of c_i deviating from its target value m; σ^2 stands for the variance of c_i; A represents the quality loss coefficient as there is a variation for c_i, and its value is standardized as 1 in this paper, for avoiding the influence on the calculation results that caused by different selections of quality loss coefficient; *TU* and *TL* represent the upper limit and the lower limit of tolerances, respectively.

Generally speaking, the variation of one alternative *PCF* at a lower assembly hierarchy would bring an influence on multiple features at adjacent higher assembly hierarchy. According to the accuracy principal, the statistical parameter $\left((\Delta_\Sigma)_0, \sigma_\Sigma^2\right)$ of the variation Δ_Σ can be calculated with the reference of the accuracy parameters $\left((\Delta c_i)_0, \sigma_i^2\right)$ of alternative *PCFs* c_i.

$$(\Delta_\Sigma)_0 = \sum_{i=1}^{n} \left(\frac{\partial F}{\partial c_i} (\Delta c_i)_0 \right) \quad \sigma_\Sigma^2 = \sum_{i=1}^{n} \left(\frac{\partial F}{\partial c_i} \right)^2 (\sigma_i)^2 \tag{7}$$

where $\partial F / \partial c_i$ represents the partial derivative.

Quality loss of the coordination feature y_m at a higher assembly hierarchy, which is caused by the variation of the alternative coordination features $c_1, c_2, \cdots, c_n$ at the lower assembly hierarchy, is shown in (8).

$$\Delta L_m = \sum_{i=1}^{n} \left\{ k_i \cdot H^2 \cdot \left[\left(\frac{\partial F}{\partial c_i} \right)^2 \left(\sigma_i'^2 - \sigma_i^2 \right) + \left(\frac{\partial F}{\partial c_i} \right)^2 \left(\delta_i'^2 - \delta_i^2 \right) \right] \right\} \tag{8}$$

With the concept of importance degree [31], it can be taken as the affected degree. Then the quality loss of the whole coordination features $Y = \{y_1, y_2, \cdots, y_m\}$ at a higher assembly hierarchy, which is caused by a single variation of the alternative coordination feature c_i at a lower assembly hierarchy, is shown in (9). And it can be taken as the influence degree.

$$\Delta L_i = \sum_{j=1}^{m} \left\{ k_j \cdot H^2 \cdot \left[\left(\frac{\partial F}{\partial c_i} \right)^2 \left(\sigma_i'^2 - \sigma_i^2 \right) + \left(\frac{\partial F}{\partial c_i} \right)^2 \left(\delta_i'^2 - \delta_i^2 \right) \right] \right\} \tag{9}$$

For the centrality degree index Z_i and the cause degree index R_i, they can be calculated as:

$$Z_i = \Delta L_i + \Delta L_m \quad R_i = \Delta L_i - \Delta L_m \tag{10}$$

And the importance degree ω_i can be modeled as:

$$\omega_i = Z_i \left(1 - R_i / \sum_{i=1}^{m} |R_i| \right) / \sum_{i=1}^{m} \left[Z_i \left(1 - R_i / \sum_{i=1}^{m} |R_i| \right) \right] \tag{11}$$

In summary, the calculation result is the direct basis to determine whether a potential alternative *CF* is the desired *PCF* or not.

B. MAPPING OF THE PCE

During the manufacturing process, *PCE* refers to the factors that affecting assembly/coordination accuracy of *PCFs*. *PCE* can provide comprehensive technical support for the coordination error controlling and adjustment process. The mapping relationship between *PCF* and *PCE* can be shown in Figure 4.

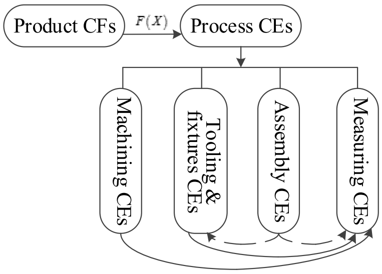

FIGURE 4. Mapping relationship between PCF and PCE.

Where $P'CE = FCE \cup TCE \cup ACE \cup MCE$.

For the mapping of machining *CEs*, i.e. *FCE*, the function can be expressed as c. Where g_f represents the mapping function of shape features, and i_f represents the function of machining intention, such as machining attributes A_{mu} and machining method A_{mv}. To determine the above process parameters, plenty of optimization works have been done for a better machining scheme.

Assembly tooling plays an important role as controlling the fluctuation of key coordination/assembly design characteristics for products. Then for the mapping of tooling&fixture *CEs*, i.e. *TCE*, two processes are mainly contained, with the consideration that assembly tooling has a close relationship with the final assembly/coordination accuracy, and the end locating effectors have a direct matting relationship with *PCF*. The first is the mapping relationship between the product assembly/coordination requirements and the comprised product feature element, and the second is the detailed mapping procedure between typical assembly components and locating method of the assembly tooling. The hierarchical structure and inference relation can be shown in Figure 5.

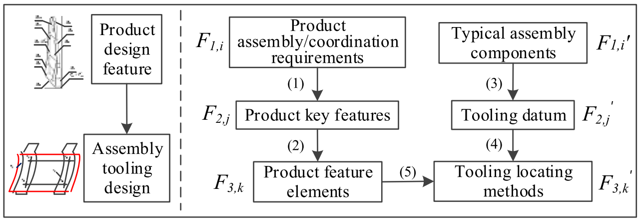

FIGURE 5. Mapping process from product design information to flexible tooling information.

It is noteworthy that the above relationship of double phase can be expressed with polychromatic set theory with a progressive way [32]. By constructing the individual color, uniform color, and contour matrix, the mapping relationship among different assembly/manufacturing hierarchies can be established. For the first layer $F_{1,i}$, considering the aircraft design features, the typical product structures that assembly/coordination problems often occur are summarized, and the relevant design structures relevant with assembly requirements can be acquired based on engineering experience and principles. Then the detailed assembly features, i.e. product key features, are defined in the second layer, expressed by $F_{2,j}$. They are the comprised elements of the product, having a direct impact on the assembly/coordination accuracy. The reference datum element layer, i.e. $F_{3,k}$, is defined as the smallest geometric element. It mainly refers to the basic geometric element, such as the features of line, plane, curved surface, and so on. It is notable that the mapping relationship between the elements of each product layer can be expressed by different contour matrix. Based on the mapping results of the first stage, the assembly feature and the feature element are concretized in the second mapping stage, i.e. the modeling object is the assembly tooling. According to (1) the assembly characteristics of different product objects, and (2) the common partition results of assembly units that caused by the process separation surface, the first layer is defined as the typical subassemblies/components, denoted as $F'_{1,i}$. On the basis of the geometric structure characteristics and the design datum of the above subassemblies/components, the locating methods for their comprised parts that frequently used are analyzed, and the tooling locating datum is expressed by $F'_{2,j}$. For the mapping process of tooling locating method, i.e. $F'_{3,k}$, considering the specific product geometric feature set, (1) the locating feasibility/stability of the product, (2) the undercarriage scheme, (3) the operation accessibility during assembly, (4) the extra enough space for tooling installation and measurement, and (5) other factors, should also be taken into account. Finally, considering all of the above mapping results, by traversing the logic mapping relations that formed in the above two mapping stages, the flexible tooling information can be obtained. Significantly, the above mapping methods can improve design efficiency of flexible assembly tooling.

For the mapping of measuring *CEs*, i.e. *MCE*, considering the form of geometric features and the corresponding error items, four main portions are mainly contained. The first is selecting the appropriate measurement devices for *PCFs/PCEs* and the process parameters during the assembly process. The second is determining the measurement datum, i.e. the part datum and the component datum. It is notable that the coordinate system of the tooling, and the measurement points planning for the component/tooling should be optimized. The third is optimizing the measuring path and the measuring sequence. The last is optimizing the sampling/distribution of measuring points. In order to explain how the measurement optimization works are carried out, two relevant research points are presented here.

The first is the optimization of ERS (Enhanced Reference System) points based on minimum bounding box. ERS points are taken as the measuring datum when establishing the assembly coordinate system. In practical assembly site, they are mounted on the assembly tooling, and their number should not be too many. Although their reasonable layout has some standard specifications, they are often determined based on experience or rules. Assembly tooling is generally composed of skeleton structures and adjustable support base. And the skeleton structures is mainly divided into frame type, combination type, and distributed type etc.. Then the optimal layout of ERS points can be carried out by means of bounding box along each coordinate axis, i.e. axis-aligned bounding box, AABB) [33], as shown in Figure 6.

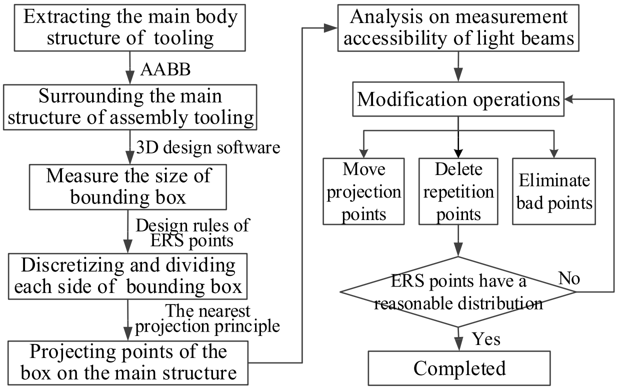

FIGURE 6. Optimization design process of ERS points.

The detailed analysis steps are described as following.

Step 1: Taking AABB as a tool to surround the overall skeleton of the tooling.

Step 2: Extracting the size of the bounding box under 3D design software (such as CATIA).

Step 3: Discretizing and dividing the dimensions of each side of the extracted bounding box, then ERS points are represented by the relevant equivalent points.

Step 4: Projecting the points of bounding box to the main structure of tooling.

Step 5: After the projection is completed, the projection points are checked according to the empirical principle of ERS point arrangement, and the analysis on measurement accessibility of light beams. Then some inappropriate points are modified and corrected, such as moving projection points, deleting repetition points, and eliminating bad points, etc.

Step 6: Checking on the distribution of ERS points with an iterative approach. Finally, the required position of ERS points could be determined.

Then with the purpose of determining the measuring points distributing on the end locating effectors and products, the overall layout planning of OTP points is optimized. Generally speaking, six freedom should be constrained to acquire the position of one rigid object. According to the "3-2-1" locating principle, the specific constraints, such as, (1) the area of the triangle that enclosed by three OTP points should be as large as possible, (2) the inner angle of the above triangle should be kept within a certain range, i.e. not too big or

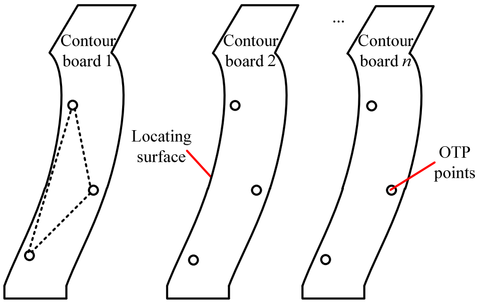

FIGURE 7. Layout relationship of the OTP points on contour boards.

too small, (3) the OTP points should be arranged as close as possible to the function area of the end locating effector. Taking the OTP points of the contour board for example, as shown in Figure 7, the detailed mathematical expression is modeled in Equation 12.

$$\begin{aligned}
&\max S_{\Delta}(P_i, P_j, P_k), P_i, P_j, P_k \in S: \\
&\angle P_i \leq \angle P_j \leq \angle P_k; \\
&\max \angle P_i, \min \angle P_k; \\
&\alpha \leq (P_i, P_j, P_k) \leq \beta; \qquad (12)
\end{aligned}$$

where S represents the working surface of contour boards, P_i, P_j, P_k stands for the three points on the flank plane of contour board, and $P_i, P_j, P_k \in S$. $S_{\Delta}(P_i, P_j, P_k)$ stands for the area of the triangle. Considering an extreme situation, if these three points are collinear, then $S_{\Delta}(P_i, P_j, P_k) = 0$. $\angle P_i$, $\angle P_j$, and $\angle P_k$ stand for three inner angles of the triangle. α and β represent the lower and upper bound of angle value. However, with the view of stability enhancement, the size of these three inner angles should be relatively the same with each other. By optimizing the size of α and β, the position distribution of the three OTP points, and the reasonable spatial position coordinates can be determined.

As last, for the mapping of assembly *CEs*, it can be neglected in Figure 4. Owing to the mapping process of *TCEs* and *MCEs*, for the following factors, such as product structure characteristic and practical assembly process, have already been contained, and they can be taken as assembly *CEs*.

C. CR MODELING

CR can be taken as the geometric constraint relationship or the precision relationship of the dimension/size/position, and it is reflected as the dimensional size, profile shape, and spatial position of assembly bodies. To model *CR*, the geometric variation of *PCFs/TCEs/MCEs* should be analyzed firstly, such as the geometric dimension/size/position. The detailed translation and rotation variation, i.e. τ, along three axes can be denoted by *SDT* (Small Displacement Tensor) theory [35-36].

$$\tau = [D\Omega]^T = \left[d_x d_y d_z \theta_x \theta_y \theta_z\right]^T \qquad (13)$$

For the matrix indicating position and posture change that caused by the *PCF's* variation, it is shown as follows:

$$T = \begin{bmatrix} \mathrm{c}\theta_z\mathrm{c}\theta_y & -\mathrm{c}\theta_y\mathrm{s}\theta_z & \mathrm{s}\theta_y & d_x \\ \mathrm{s}\theta_x\mathrm{s}\theta_y\mathrm{c}\theta_z+\mathrm{s}\theta_z\mathrm{c}\theta_x & -\mathrm{s}\theta_x\mathrm{s}\theta_y\mathrm{c}\theta_z+\mathrm{c}\theta_z\mathrm{c}\theta_x & -\mathrm{s}\theta_x\mathrm{c}\theta_y & d_y \\ -\mathrm{s}\theta_y\mathrm{c}\theta_x\mathrm{c}\theta_z+\mathrm{s}\theta_x\mathrm{s}\theta_z & \mathrm{s}\theta_y\mathrm{c}\theta_x\mathrm{c}\theta_z+\mathrm{s}\theta_x\mathrm{c}\theta_z & \mathrm{c}\theta_x\mathrm{c}\theta_y & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (14)$$

To the different kinds of *CR* in aircraft assembly, the curved surface-surface matting relationship and hole-pin matting relationship are mostly used. The matting relationship refers to the geometric relationship of different features, such as the curved surface, the hole axis, and the plane surface, etc., when assembling parts together. It also can be called as matching relationship among different geometric features. Under the local coordinate system CS_L (O_L, X_L, Y_L, Z_L), given the expression of one curved surface is $C_L = C_L(u, v)$, its deviation can be shown in Figure 8.

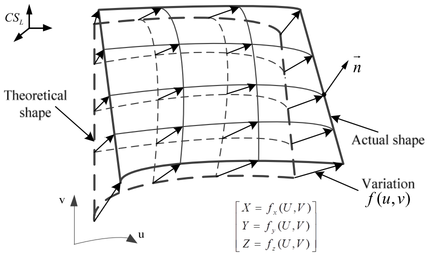

FIGURE 8. The deviation of curved surface.

As modeling CR, the actual surface is usually replaced by a new fitting surface, according to the measurement data. Given the deviation value is expressed as $f(u, v)$, then the deviation in CS_L (O_L, X_L, Y_L, Z_L) can be expressed as: $F_L(u, v) = C_L(u, v) + f(u, v) \cdot \vec{n}$. Where $\boldsymbol{n}$ represents the normal vector on the tangent plane at the feature point.

For the curved surface-surface matting constraint, this deviation can be shown in Figure 9, and it can be calculated as:

$$\Delta \vec{r}_{face-face} = \vec{r'} - \vec{r} = \xi_1 \vec{n_1} - \xi_2 \vec{n_2} \qquad (15)$$

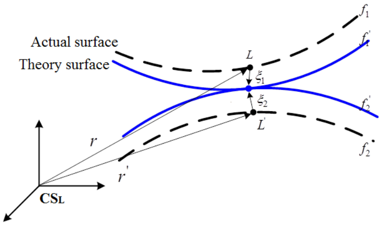

FIGURE 9. The curved surface-surface matting constraint.

For the hole-pin matting relationship, the position variation and diameter variation should be taken into account, as shown in Figure 10. Without the consideration of the variation along z direction, given the position error of the pin is $\xi_1^{pos} = [\xi_{1x}^{pos}, \xi_{1y}^{pos}, 0]^T$, for the hole is $\xi_2^{pos} = [\xi_{2x}^{pos}, \xi_{2y}^{pos}, 0]^T$, then

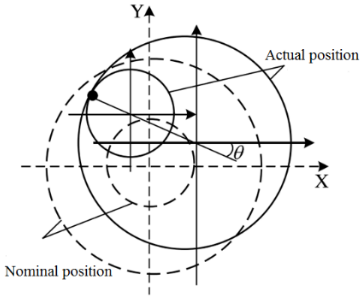

FIGURE 10. Matting relationship for the hole-pin matting relationship.

their matting variation is: $\Delta r^{pos} = \xi_1^{pos} - \xi_2^{pos}$. Given the diameter variation of hole is Δw_1, and Δw_2 of the pin, respectively. Their matting clearance can be calculated as: $\delta^d = (w_2 + \Delta w_2) - (w_1 + \Delta w_1)$. Due to the matting angle for this assembly relationship, this error item is discomposed along the x and y axes, shown as: $\Delta r^{size} = [\delta^d \cos\theta, \delta^d \sin\theta, 0]^T$. With the consideration of position error Δr^{pos} and dimension error Δr^{size}, the comprehensive error deviation $\Delta r^h_{hole-pin}$ for the hinge joint is calculated as: $\Delta \vec{r}_{hole-pin} = \Delta\overrightarrow{r^{pos}} + \Delta\overrightarrow{r^{size}}$.

D. ASSEMBLY ERROR PROPAGATION MODELING

In this section, the following items are considered, i.e. error modeling, error interaction relationship, assembly precision propagation modeling at a single station, and assembly error chain construction. By calculating the accumulation error of a single sub-assembly object, the matting size and shape between different assemblies can be judged [31].

As modeling the basic error sources in assembly process, the part manufacturing error can be represented as a normal probability variable $\xi_p \sim N(\mu_p, \sigma_p)$, as already shown in Equation 5. With the help of measuring operations, the positioning error of assembly tooling also has distributions of $\xi_f \sim N(\mu_f, \sigma_f)$. For deformation error item ξ_d, it can be gained according to FEM (Finite Element Simulation) method considering the practical working constraints or conditions. In practical assembly site, it is notable that the establishment error of assembly fixture CS (Coordinate System) has a direct relationship with ξ_f for end locators. The accurate transformation parameters should be expressed directly, as shown in Figure 11.

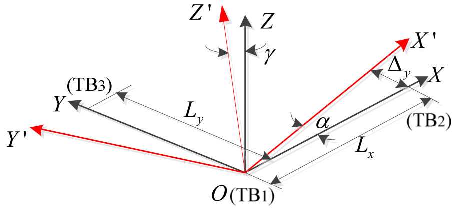

FIGURE 11. Axes errors in assembly fixture CS.

The actual rotation angle γ for z-axis can be determined by the normal vector of *XOY* plane. Assume that the coordinate of the first TB (Tolling Ball) point is $(0, 0, z_1)$, and the coordinates of $(L_x, 0, z_2)$, $\left(0, L_y, z_3\right)$ are for the other two TB points, then the normal vector $\vec{n}$ of the practical *XOY* plane can be gained as $\vec{n} = \left(L_y(z_1 - z_2), L_x(z_1 - z_3), L_x L_y\right)$. Where the TB points are mounted at the four corner of the base plane of the assembly tooling, and the main structure of assembly fixture can be covered. TB points are taken as the measurement datum for establishing tooling reference system only. And it is notable that TB and ERS points only occur in assembly tooling system. Then the rotation angle $\Delta\alpha$ and $\Delta\beta$ for the x-axis and y-axis can be represented by Equation 16, where Δx and Δy represent the position error of the measuring datum points along the directions of x and y axes, respectively. Lx and Ly represent the distance of the measuring points along the above two axes.

$$\begin{cases} \Delta\alpha \approx \Delta_y / L_x \\ \Delta\beta \approx \Delta_x / L_y \end{cases} \tag{16}$$

In the propagation process of assembly errors, the above three kinds of basic error would interact with each other. For the interaction relationship between ξ_d and ξ_f, the parts would be translated and rotated, due to the existence of matting error δq. With the analysis methods of *DLP* (Deterministic Locating Principle), Mentor Carlo simulation, and FEM, the statistical properties of δq can be gained. Where $\delta q = [S]\left(\xi_f - \xi_p\right)$, and $[S]$ represents the error sensitivity matrix. It is noteworthy that, for different assembly stages, or different working procedures at a certain assembly stage, δq at the previous assembly stage may be an input error for the following error ξ_d. Under this situation, a new error item of influence error θ_i would occur, which can be modeled with *GCP* (Geometric Continuity Principle). For another situation, ξ_d at the previous assembly stage would also affect the current mating error δq, both at the direction of translation and rotation with the coordinate axes. Under this situation, a new influence error ρ_i would also occur, which can be solved with the analysis on error transformation and rotation matrix. In a word, the above influence would make the propagation of assembly error a non-linear relationship.

Then for the assembly work at one single assembly station k, it is the accumulation process for the parts to be assembled on the semi-finished assemblies. Considering the *SSM* (State Space Model) method, the assembly error propagation chain can be taken as the accumulation of the above error items, expressed as:

$$\begin{aligned} [X_k]_0 &= F\left(\xi_p(k), \xi_f(k), \xi_d(k)\right) \\ &= \delta q(k) + \xi_d(k) + \psi(k) + \rho(k) \end{aligned} \tag{17}$$

It is noteworthy that with the comprehensive application of the above four controlling methods, the assembly coordination error should meet the design requirements. If not, with the instruction of SPC method, the four quality control process should be done for another time on the detailed comprised error items. Then the assembly production process is comprehensively adjusted, and the coordination error links that having a significant influence on assembly /coordination accuracy, can be optimized and adjusted with a feedback loop to improve the assembly error.

IV. ASSEMBLY STATION FLOWING FLUCTUATION ANALYSIS AT DIFFERENT TIME STAGES

With deviation control chart, by analyzing the quality characteristics during the manufacturing and assembly process, the SPC method can be used to distinguish whether the process is in a stable status. Then with the detailed qualitative and quantitative analysis on the distribution and the trend of abnormal conditions, benefit adjustment results can be gained for the specific assembly process. However, the above SPC charts are mainly focusing on the product quality characteristics under one certain fixed assembly station, and reflecting whether multiple quality samples are in a statistical stable state. Because of the small amount of the produced aircraft products, for the process deviation and fluctuation of a single quality sample under a statistical stable state, little attention has been paid on the quality data items at the same assembly station, the same assembly process, but not on different time stages. In practical assembly, the values of one type of quality sample at different assembly stations (i.e. the same assembly process at different time stages, such as parallel assembly lines) may also not the same, and they change dynamically over time. Then the SPC chart would not reflect this situation. For the shape and dimension transferring process in aircraft manufacturing, in order to further analyze the fault source and improve the process flowing, the concept of ASFF is proposed with the perspective of production statistics. ASFF is mainly fitting for the deviation and fluctuation of assembly results under one certain assembly station at different time phases.

[Definition 1]: Assembly Station Flowing Fluctuation (ASFF)

The core viewpoint of ASFF is similar to the PVTC that used in CNC machining process. In aircraft manufacturing process, with regard to one component at a certain assembly station within different time stages, ASFF refers to the expression of the trajectory diagram for the dynamic change of the quality characteristics. And it is comprised by the fluctuation analysis on assembly quality samples. With ASFF, the quantitative evaluation for the capacity of flowing fluctuation during the whole assembly station can be achieved. As a result, the assurance ability of assembly station for product assembly quality is to be improved eventually.

To understand the concept of ASFF with more clarity, some extensional explanations on relevant terminologies are stated as following.

(1) Deviation rate of assembly process

As well known, the excessive deviation of the mean value during the assembly process would lead to product quality defects. Generally speaking, for the product assembly quality characteristics of the mean value and its design requirements, there exist a certain degree of deviation. A relative offset rate is proposed in order to reflect the deviation degree between them. And the deviation rate of assembly process can be denoted by Δd_{ij}, as shown in Equation (18).

$$\Delta d_{ij} = \frac{\overline{X_{ij}} - \mu_{ij}}{D_{ij}} = \frac{\frac{1}{N}\sum_{k=1}^{N} X_{ijk} - \mu_{ij}}{\left(USL_{ij} - LSL_{ij}\right)/2} \tag{18}$$

For the above Equation, where X_{ijk} represents the k^{th} measurement value of the j^{th} quality characteristic at the i^{th} assembly station, $\overline{X_{ij}}$ represents their average value, μ_{ij} stands for the target value of the j^{th} quality characteristic at the i^{th} assembly station, USL_{ij} stands for the upper deviation limit, LSL_{ij} stands for the lower deviation limit, D_{ij} represents the centerline of the upper and lower deviation, and N stands for the number of measurement samples.

(2) Stability of assembly process

During the aircraft assembly process for one certain component, the fluctuation of quality sample has a significant influence on the consistency of different assembly errors and the stability of assembly quality. The Equation (19) can be used to describe the function effectiveness, with which the relative stability coefficient of the manufacturing process, i.e. Δs_{ij}, is adopted, and the fluctuation of the assembly station status flowing can also be expressed.

$$\Delta S_{ij} = \frac{\sigma_{LT_{ij}} - \sigma_{ST_{ij}}}{\sigma_{LT_{ij}}} = \frac{\sqrt{\sum_{k=1}^{n}\left(X_{ijk} - \overline{X}_{ij}\right)/(n-1)} - R_S/d_2}{\sqrt{\sum_{k=1}^{n}\left(X_{ijk} - \overline{X}_{ij}\right)/(n-1)}} \tag{19}$$

With regard to the above equation, where d_2 represents a constant value. d_2 is determined by the size of the sample group, and Δs_{ij} has a variation range value of [0,1]. $\sigma_{LT_{ij}}$ represents the long-term standard deviation, and $\sigma_{ST_{ij}}$ represents the short-term standard deviation.

[Definition 2]: Trajectory Chart of Assembly Station Flowing Fluctuation

Considering the factors of the quality changes among different assembly time stages or different aircraft products, then for the deviation and fluctuation of the quality characteristics at a certain assembly station, they would form a fluctuation curve on the established fluctuation plane, namely the station fluctuation trajectory diagram, as shown in Figure 12. The trajectory chart can be expressed by quality coordinates at different assembly stations. Where the quality coordinate is denoted by $(\Delta d_{ij}, \Delta s_{ij})$. Δd_{ij} stands for the value that shown by the x-axis in the two-dimensional fluctuation plane, and Δs_{ij} is shown by the y-axis, respectively. Where the two fluctuation trajectories of two assembly stations at four different time phases are contained.

For the fluctuation trajectory of certain assembly station, it is notable that the division of fluctuation area for each station is determined by the six sigma quality theory. For the region I in Figure 12, the horizontal axis and vertical axis

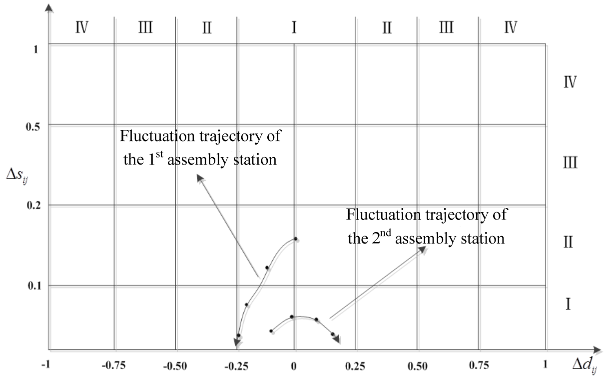

FIGURE 12. Fluctuation trajectory of two assembly stations.

stand for the normal offset of the deviation and a status that in a stable status, respectively. For the region II, it represents the deviation is large and the quality status is less stable. However, for the regions III and IV, the deviation becomes larger, and the quality status becomes more unstable. When some quality samples locate in regional II, or even in regional III, it needs to solve the deviation problem at the current assembly station, i.e. it needs to further reduce the process fluctuation and deviation value. Other wisely, the assembly quality of the products would be not so good and have an obvious inconsistency, and it even cannot meet the design accuracy requirement.

The trajectory chart is firstly proposed in this paper aiming to reflect the quality characteristics for one certain assembly station, i.e. the quality deviation and fluctuation state. With the analysis on the chart, the detailed improving opportunities and strategies for each assembly stations can be acquired. As the quality data of the two assembly stations that shown in Figure 10, the deviation at the 1st station has a tendency of gradually increasing, but the fluctuation degree has a tendency of gradually decreasing. After analyzing on these situations, it is found that the function effect of systematic errors in the assembly/manufacturing process is increasing, attentions should be paid to eliminate it. It is summarized that the systematic error is mainly contained by the change of physical environment such as temperature/gravity, or the operator skill level, or the drilling/jointing deformation, etc.. However, at the 2nd assembly station, the deviation and fluctuating status are staying in the normal range, and the corresponding assembly operations are supposed to be maintained at the current level.

To summarize this chapter, for multi-components, by analyzing the fluctuation trajectory of one certain assembly station at different time stages, when the deviation value of the fluctuation state and the quality characteristic exceed the desired numerical value, some corresponding solutions should be taken. Benefit results would be gained with the analysis on the quality trend that displayed intuitively, such as the assembly process at different time stages would be more stable, the fluctuation of quality characteristic is to be more and more consistent, and the error coordination consistency among different assemblies would be better. With the analysis on the large amount quality samples, the above optimization solutions would be much helpful in aircraft batch production.

V. EXPERIMENT VERIFICATION

A. STRUCTURE OF THE EXPERIMENTAL OBJECT

There are four wing flap components in a certain type aircraft, i.e. the inboard, the outboard component and the other two exactly symmetrical with them. The main parts are separated as ribs, spar(s), hinge joints, skin panel etc., as shown in Figure 13. The two components would be joined together at the interface of 14th rib and the 15th rib to be a complete component [31]. On the macroscopic, the position and number of ribs that distributing on the spar are different from the inner one and the outer one.

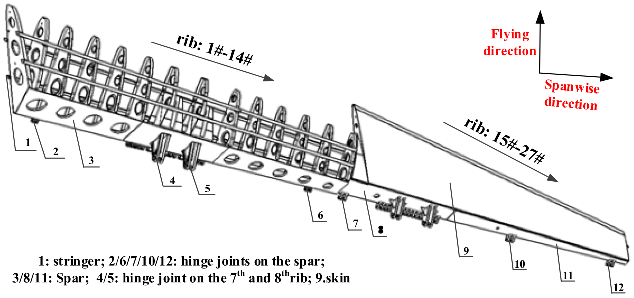

FIGURE 13. Structure of the wing flap components.

B. PCF IDENTIFICATION AND THE QUALITY DATA MEASUREMENT SAMPLING

According to the design requirements and the official assembly document, the flush coordination accuracy between skins of inner component and outer component should be guaranteed in the assembly process. The flush is defined as the offset or altitude difference between the two different skin profiles. Based on the theory analysis mentioned in Section III, the quality loss ΔL_m of the skin profile at the ending ribs is calculated. According to the calculation method of centrality degree index Z_i and cause degree index R_i, the results of complete importance degree of the skin profile for the inner component and the outer component are $\omega_1 = 0.45$, and $\omega_2 = 0.55$, respectively. The results indicate the skin profile of the comprised inner and outer components are the *PCFs* that needing to be guaranteed. And it has a tight relationship with error status of the comprised parts, such as spar, rib, stringer, and skin profile.

Considering the 1st rib and the 16th rib have the similar (1) geometric dimension, (2) geometric shape/profile, (3) the required assembly profile error, and (4) the detailed positioning or assembly method, then taking another five factors in account, i.e. (1) the left and right components are exactly symmetrical about the design datum of the aircraft, (2) the installation and adjustment work of the assembly jig is completed by the same bench workers, (3) the assembly

TABLE 1. Statistical data information of the profile deviation for the ending ribs (mm).

Quality sample	1	2	3	4	5	6	7	8	9	10
	01st flight					03rd flight			04th flight	
X	0.36	0.38	0.40	0.08	0.27	0.35	0.32	0.33	0.35	0.39
R_s		0.02	0.02	0.32	0.19	0.09	0.03	0.01	0.02	0.04
Quality sample	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	04th flight			06th flight				08th flight		
X	0.29	0.31	0.18	0.24	0.29	0.17	0.28	0.26	0.35	0.20
R_s	0.10	0.02	0.13	0.06	0.05	0.12	0.11	0.02	0.09	0.15

process level for the technicians that responsible for the inner and outer component is roughly the same, (4) the assembly work starts at the same time, and (5) the assembly tooling and assembly environment is proximately the same for different components, the assembly analysis work can be done. It is noteworthy that the above nine assumptions are correspond to the regular assembly operations on-site. By integrating these nine factors comprehensively, a conclusion can be drawn, namely the manufacturing normative requirements of the four components are basically the same. As a result, the measurement and test data for the skin shape of the ending ribs of the four components, can be combined together to construct the simulated sample data in the statistical process control process. Correspondingly, the number of samples can also be expanded, which also means they are the same kind quality data at different assembly time stages or stations. In the practical production, by recording the measured skin profile data of the four ending ribs of five different aircraft products, i.e. the 01st, 03rd, 04th, 06th and 08th, a simulation sample that containing twenty data points is constructed. And with the Equations presented in the second Section, the samples' statistical data information is calculated and analyzed, as shown in Table 1.

In practical assembly site, it is notable that the measuring equipment for collecting the sample data of the skin profile is laser tracker, namely API III. To measure the above source data and define the profile deviation with the data from laser tracker, seven important steps are adopted and described in detail, as shown in Figure 14.

Step 1: Establish the coordinate system of assembly fixture. In the assembly system, there are four *TB* datum measurement points distributing at the corners of the adjustable support foundation. The first three *TB* points are adjusted to the same height with a special device, namely gradienter. Then the CATIA model of the assembly fixture is delivered to measurement software *SA* (Spatial Analysis) that exclusive used with laser tracker. And this software can streamline the process of evaluating the deviations and their minimization, such as best fit. After the position of TB1 is fixed, and with the method of shaft alignment, the position of *TB2* is adjusted along y direction. Correspondingly, the X axis of the fixture coordinate system is determined. With the same method, after the position of *TB3* along x direction is fixed, the Y axis is also determined. For the Z axis, it can be determined automatically with the guidance of right-hand principle, based on the obtained X/Y axes. Thus, the Cartesian coordinate system of tooling system, i.e. $OXYZ$, can be automatically generated in the laser tracking measurement system. It is noteworthy that the fourth TB point has a function of checking and adjusting the built reference system. Then the assembly measurement work can be carried out.

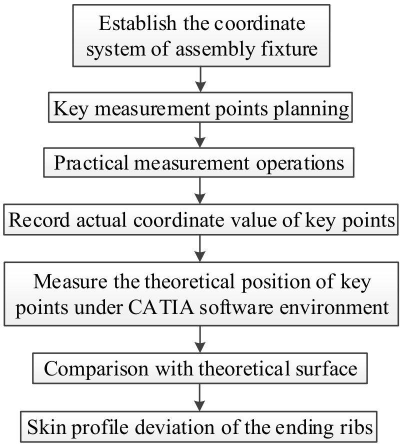

FIGURE 14. Measurement procedure on the profile deviation for the ending ribs.

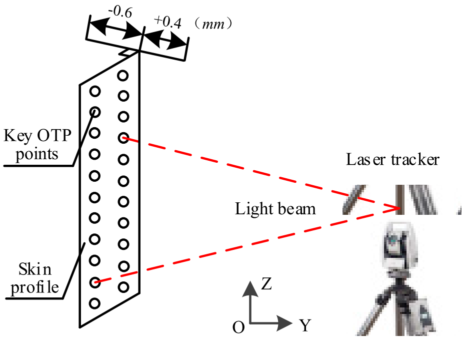

FIGURE 15. Key measurement points planning at the ending rib.

Step 2: Key measurement points planning. For the skin profile of the ending ribs, due to the surface curvature does not change drastically, 22 key OTP measurement points are planned in practical assembly site, as shown in Figure 15.

The method of equidistant measurement is adopted, i.e. the distance between two adjacent points is 1/11 of the part's length. These points are distributed uniformly along the flying direction by two rows, nearly covering the whole regions of skin profile at the ending rib.

Step 3: Practical measurement operations. Under the practical assembly environment, in the tooling coordinate system, for each ending rib, measure the position of each key OTP points ($P_i = (x_i, y_i, z_i), i = 1, 2, \ldots, 22$) ten times with a laser tracker.

Step 4: Record the actual coordinate value of key points. The average coordinate value of each P_i is noted as $\overline{P_i} = (\overline{x_i}, \overline{y_i}, \overline{z_i})$, and it is taken as the actual coordinate position status, with the purpose of minimizing the measurement error.

Step 5: Measure the theoretical position of key points under CATIA software environment. The mathematical model of the components is imported into the CATIA virtual assembly environment, then the theory coordinate of key measurement points that distributing on assembly platform can be gained in the virtual software. Where the theory coordinate value of each OTP points is recorded as $P_{i0} = (x_{i0}, y_{i0}, z_{i0})$.

Step 6: Compare the theory data of OTP points with the real-time measured results. Calculate the difference between $\overline{P_i}$ and P_{i0}, record the result as $\Delta P_i = (x_i, y_i, z_i)$.

Step 7: Calculate the skin profile deviation of the ending ribs. The profile deviation is taken as the average $\Delta P_i = (x_i, y_i, z_i)$ of all the key OTP points, i.e. $\Delta P = (\sum_{i=1}^{22} \Delta P_i)/22 = (\Delta x, \Delta y, \Delta z)$.

For the measurement results in Table 1, there are three aspects need to be explained.

- It is known that the profile deviations along the vertical direction has the most important influence on the flight performance. As a result, only one value, not three, is taken as the representation of the entire assembly deviation of the skin profile.
- The positive measurement value indicates the skin profile is large than the theoretical shape, and vice versa.
- By browsing the assembly technique documents, the desired assembly deviation has a range of [*−0.6mm, +0.4mm*]. Combining with the measurement characteristic of laser tracker, the deviation results in Table 1 displaying as two decimal places.

C. ASSEMBLY QUALITY CONTROLLING WITH SPC AND FEEDBACK IMPROVEMENT ACTIONS

Based on the above statistical data listed in Table 1, the individual value range control chart, i.e. $X - R_S$, is drawn according to Equations (1) to (4), as shown in Figure 16 and Figure 17.

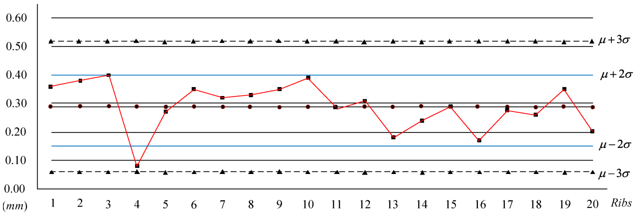

FIGURE 16. **The individual control chart for the skin profile characteristic.**

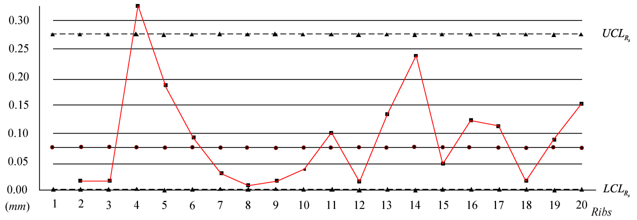

FIGURE 17. **The moving range control chart for the skin profile characteristic.**

As shown in Figure 16, for the ending rib of the left outer wing flap in the first measurement data set, it can be observed that the position of the skin profile measuring points fall on the upper and lower control line area in the individual value control chart. Then by observing the Figure 17, it can be seen that the measuring results of the profile deviation for the ending ribs exceed the upper and lower control line in the moving range control chart. Based on the distribution form of the above quality sample, it can be judged that there are abnormal situations existing in the manufacturing and assembly process. The improvement solution can be benefit from the first criterion that mentioned in Section II, i.e. "Analysis on SPC chart in aircraft assembly with qualitative practical experience". And the obvious shortcomings of the assembly scheme are analyzed.

As a matter of fact, in the practical assembly work of the wing components, the ending ribs are located with the help of a dedicated rigid assembly tooling. More specifically, the ribs are positioned by the positioning block that mounted on the counter boards along the spanwise direction, and the ribs are also positioned by a movable block with a gap of skin thickness along the flying direction. It is noteworthy that the position of the movable block is adjusted manually by taking the actual precision or position status of the ribs into account. The above operation is carried out according to the worker's experience. This manual method is result in the limitation of design skills on the rigid assembly jigs [35], about 20 years ago. And the traditional analog assembly technology has a low digitization degree. As assembling the wing flap component, shown in Figure 18, positioning method based on contour boards is often adopted. Where f_1 represents the rib's profile, f_2 represents the contour board, f_3 represents the theoretical contact surface between rib and contour board, f_4 represents the actual contact surface between the above two kind of parts, ∇ represents the assembly error between the ending rib and its positioning tooling. Although the assembly equipment has achieved the pre-defined accuracy and stability before it has been taken over in the assembly process, the behaviors caused by the assembly operations, such as assembly deviation and deformation resilience, would make the assembly quality of complex thin-walled structures always difficult to guarantee.

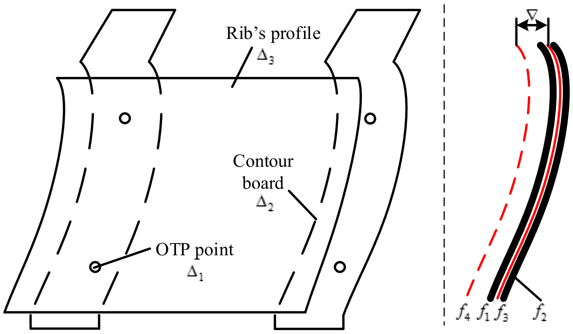

FIGURE 18. Positioning method based on contour boards.

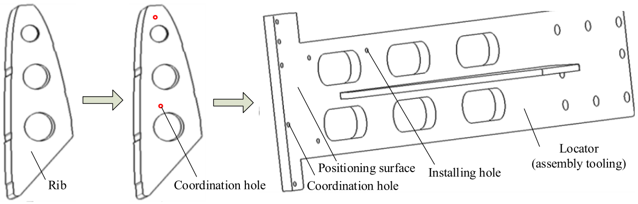

FIGURE 19. Positioning method based on coordination holes.

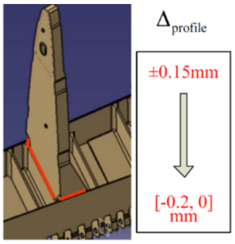

FIGURE 20. Optimization of the tolerance information between the rib and the spar.

In order to address the above problem and decrease the fluctuation range, by taking the detailed solutions that presented in the second chapter, and the Section of III "Mapping of the *PCE*" and "*CR* modeling", one efficient action is taken in practical assembly site, i.e. one special positioning device for each end wing rib is designed and added, as shown in Figure 19. Considering the mating holes has a simple assembly relationship compared with the profile of contour boards, the positioning method based on coordination holes is proposed. Coordination holes that distributing on the rib and the locator have the same dimension and position in the unified coordinate assembly system, and they appear in couples. Front area of the two flanks of the locator is used for locating the rib's web, on which existing two coordination holes. The coordination holes can also be used as optical target points as locating the rib with a laser tracker. The above assembly method, i.e. one-surface-two-holes, can improve the low assembly accuracy and avoid many of the assembly problems with contour boards. The assembly statistics result of the following four data sets showing that the assembly quality is obviously improved by taking the above solution.

For the individual control chart, i.e. Figure 16, it can be known that, for the assembly work of the first three products, the position of most measuring points distributing on the skin profile falls above the center control line. Considering the lower assembly deviation control limit, i.e. $-0.6\ mm$, its absolute value is greater than the upper assembly deviation control limit, i.e. $+0.4\ mm$, solutions should be taken in order to make the position of measuring points in the chart move toward the lower limit, with a low overproof risk. And one efficient solution is taken to decrease the deterministic systematic errors, with regard to the above phenomenon. To be more specific, the solutions can be benefit from the criterion that described in Section II. In practical assembly site, for the matting process between the rib and the spar that shown in Figure 13, there is a phenomenon that the rib often has a position deviation in the flying direction. The above position deviation would cause a large coaxiality error between (1) the mounting hole on both ends of the counter boards, and (2) the locating hole on the bracket of the assembly jig. Then the locating pins that passing through the above two holes would be in an inflexible rotational state. In extreme cases, the pins couldn't be inserted or would block. To solve this problem, the quantitative optimization solutions that described in Figure 3 are taken into account, and continuous improvement actions are taken, such as (1) modeling the coordination relationship of pin-to-hole according to the practical error status, (2) calculating the error chain of skin profile by taking all of the error items into account, i.e. the manufacturing error, the tooling error, the assembly error, etc., and (3) diagnosing the coordination error sources with a hierarchical cooperative way.

Then the tolerance information between the rib and the spar can be redesigned, and controlled within a reasonable value with an active feedback method, as shown in Figure 20. By browsing the official assembly documents, the machining error of the two matting parts is $\pm 0.15\ mm$. With the instruction of Sections III, according to the *CRs* of the corresponding geometric features, the assembly precision of key OTP points distributing on the rib profile can be calculated by Equation (20). Where α stands for rotation angular deflection at the sleeve mating area (denoted by the red line).

$$\Delta_{profile} = \Delta_{rib-spar} \times \Delta_{\alpha} = [-0.029, +0.171]mm \qquad (20)$$

It can be known the calculated result takes a large portion of the desired assembly deviation range. To loose the tolerance range of other error links, with the instruction of Sections III, the error of the above two parts is optimized to $[-0.2, 0]\ mm$. With this solution, the locating pins have a flexible rotational state, and the quality data of the 4th and 5th products showing a massive opposite tendency, which means the assembly quality is getting improved.

To sum up this section, with the above optimization actions, firstly, the locating pins that working with the counter boards would have a relatively flexible rotation performance. And then, for the assembly work of the following aircraft products, the assembly error becomes easier to guarantee.

With another aspect, the measuring points of the skin profile at the position of the ending ribs, i.e. the 4th and 5th data samples, would locate below the central control line, and also more closer to the centerline of required assembly deviation range. In practical assembly site, similar solutions are also adopted on the matting area of other ribs and spars, and the skin profile deviation can both fit the design requirements with the theory analysis and practical measurement.

D. ASSEMBLY QUALITY CONTROLLING WITH ASFF ANALYSIS

For the purpose of guaranteeing the assembly quality, some other solutions are also taken with ASFF analysis. For the assembly work of certain products, relevant analysis proceedings on the skin profile of the ending ribs for the four components have been done. The dynamic change of the assembly quality at different time stages is taken into account. Before adding the specific locating device for the ending wing ribs, and optimizing the tolerance information between the rib and the spar, the quality characteristics data of each coordination feature at six different time periods are collected, i.e. the deviation of the skin profile samples at the ending ribs, as shown in Table 2.

TABLE 2. Statistical data of skin profile at the ending ribs (mm) (without assembly quality controlling actions).

Time periods Quality sample	1	2	3	4	5	6
Q_{in-r}	0.28	0.18	-0.21	-0.35	0.24	0.34
Q_{out-r}	0.26	0.25	-0.19	0.18	-0.27	0.17
Q_{in-l}	0.35	-0.24	0.13	-0.26	0.18	0.24
Q_{out-l}	0.20	-0.22	0.24	0.14	0.23	0.18

As illustrated earlier in Table 2, where Q_{in-r} stands for the quality characteristic of the right inner component, Q_{out-r} represents the quality characteristic of the right outer component, Q_{in-l} represents the quality characteristic of the left inner component, Q_{out-l} stands for the quality characteristic of the left outer component. Through the calculation work as shown in Equations (18) and (19), the distribution results of the above four kind quality characteristics' fluctuation situation can be shown by the dark dots in Figure 21, i.e. the upper region of this graph.

Through observation on Figure 21, according to the analysis in the Section IV "Assembly station flowing fluctuation analysis at different time stages", it can be known that the process deviation of the above four quality features is large, and the assembly process is unstable. However, after adding the special positioning locators that having a locating function on the ending wing rib, and optimizing the assembly parameters, the practical data of each quality features that collected at six different assembly periods is shown in Table 3. And then after adding the above actual data into Equations 18 and 19 for calculation, the fluctuation results can be shown by the light-colored dot in Figure 21, i.e. the lower region of the graph.

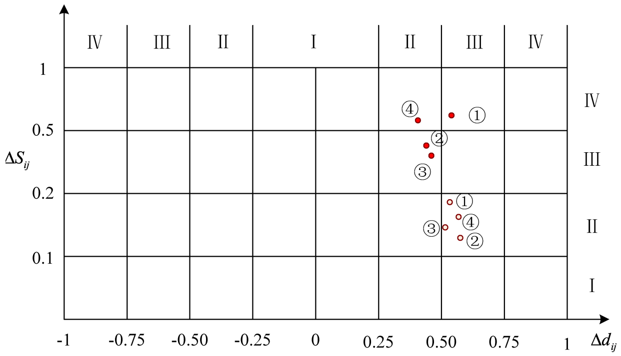

FIGURE 21. Assembly station flowing fluctuation diagram of the wing components.

TABLE 3. Statistical data of skin profile at the ending ribs (mm) (with assembly quality controlling actions).

Time periods Quality sample	1	2	3	4	5	6
Q_{in-r}	-0.35	-0.22	-0.21	-0.19	-0.34	-0.25
Q_{out-r}	0.17	0.35	0.28	0.34	0.33	0.19
Q_{in-l}	-0.25	-0.34	-0.21	-0.19	-0.31	-0.22
Q_{out-l}	-0.22	-0.24	-0.18	-0.29	-0.36	-0.40

With the analysis work that mentioned above, it can be concluded that after taking the assembly quality controlling actions, the average process deviation of quality features still have a large numerical value, from 0.128 mm to −0.134 mm. And further optimization and improvement actions should be done. Such as the redesign and relocation of the part design error, the tooling installation/locating error, the assembly deformation error, datum transformation error, and so on. However, to show the optimization results, the deviation rate of assembly process Δd_{ij} is changed from 0.473 to 0.525, its fluctuation range is $(0.525 - 0.473)/0.473 \times 100\% = 10.994\%$, which is acceptable in practical assembly site. The stability of assembly process, i.e. Δs_{ij}, is changed from 0.46 to 0.16, its increase range is $(0.460 - 0.160)/0.460 \times 100\% = 65.217\%$, which means the optimized assembly process is more stable, and the assembly quality is improved by adopting the above benefit actions.

E. DISCUSSION

Based on the proposed methodology for assembly quality controlling, the out-of-tolerance problem for the skin profile is optimized in this section, aiming at verifying methodology's feasibility. It is notable that, for the above aircraft assembly quality control with feedback actions and ASFF analysis, its working mode is offline. There are the following explanations.

Firstly, the theme of this article is to (1) further analyze the fault source and improve the assembly process operations, (2) pay attention to the dynamic deviation and fluctuation of assembly results within a specified assembly station, (3) improve the assurance ability on assembly quality. It is more available for a relatively stable production process, for example, the batch manufacturing. The quality control methods of SPC and ASFF, are also more suitable for statistical analysis of assembly results, and they can provide benefit improvement solutions for the subsequent products.

Secondly, for most of the aircraft manufacturing companies, due to the actual production ability and the assembly conditions, it is always difficult to gain enough assembly data samples in practical assembly workshop. It is also known that the online controlling method needs the support of a great deal of data. And this maybe one of the most important reasons for the control method works not online.

Thirdly, with the help of Section III, a lot of optimized assembly parameters are gained. However, for complex products, such as aircraft, they often are comprised by lots of large sheet metal panels/parts with a weak rigidity and a complicated shape/structure, this would cause the assembly quality optimization and controlling a heavy calculation task, and the online working mode is difficult to accomplish.

Although the quality control method works offline, the effectiveness in practical assembly site can also be gained. The first is reflected by the benefit improvements that carried out in assembly process. For example, by (1) diagnosing the abnormal sources and improving the assembly operating process, (2) analyzing the dynamic deviation and fluctuation of assembly quality data within a specified assembly station, and (3) improving the assembly assurance ability. To be more specific, as shown in Section V.C, the positioning method for the ending ribs, and the relocation of tolerance information between the rib and the spar, are improved. The other aspect is reflected by the actual measured assembly results. In practical assembly site, after analyzing the assembly results, it is found that the locating state of ending ribs is more accurate, the assembly process becomes more stable. And the calculated theoretical assembly error of skin profile fits well with the practical assembly measurements, and they can also meet assembly accuracy requirements. In conclusion, the above benefit results would be much helpful for the assembly quality improvement, especially in the batch production process.

VI. CONCLUSION

In this paper, one assembly quality controlling method for key characteristics of aircraft products with feedback actions and ASFF is studied. The main conclusions are as follows.

1. With SPC analysis, assembly feedback actions, and ASFF analysis, the assembly quality controlling in practical production process is completed, and some specific benefit improvement actions are put forward with the comprehensive use of the above qualitative and quantitative methods.
2. For the out-of-tolerance problem of the skin profile at the ending ribs, the assembly deviation data of five aircraft products are analyzed with quality controlling methods. The quality characteristic at another six time periods are compared and analyzed, with the optimization actions, such as adding the specific locating devices for the ending ribs, and relocating the matting errors between the rib and spar. Benefit results are gained, i.e. the assembly quality can meet the design requirements, and the assembly process is more stable.
3. With regard to other complex products, such as rocket, automobile, etc., it is notable that there are many factors relating with the optimal analysis on the assembly quality, and there still exits various further difficulties to be solved in practical manufacturing process. How to make the optimal decision based on the real-time [40-42] measuring data considering the intelligent analysis and decision making methods, and the data analysis software, is the urgent research work to be done in the next step.

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