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MOTION STROKE DESIGN ON FLEXIBLE ASSEMBLY TOOLING FOR MULTIPLE AIRCRAFT COMPONENTS

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Abstract

To get an accurate dimensional size/shape/spatial and assembly accuracy, flexible assembly tooling is developed and applied in aviation production, instead of traditional dedicated rigid tooling. Its configuration can be adjusted to fit different assembly environments and support/locate different components together in correct relative positions. For multiple aircraft components, the optimal design on flexible assembly tooling system, i.e. motion stroke of each comprised locating units, was studied in this paper. Considering the constraints of assembly operation space, assembly constraints (such as gravity, assembly loads, locating freedom, etc.), product posture, and other specific assembly factors, a design procedure with quantitative analysis was described for solving the problem. Eleven steps were contained and modeled, and then solved with intelligent algorithm. The first core problem was to determine the number and the accurate distribution of the locating points reasonably, with a minimum assembly deformation. For aviation parts with thin-walled structure, the special locating layout planning scheme, i.e. $(N= N_1+N_2)+2+1(N\geqslant 3)$ principle, was proposed. Where N_1 was determined by the pre-existing geometric limitations of the product features, N_2 was obtained with the optimization solution under the number and position of constraint N_1. Then the assembly position of each locating unit can be confirmed. The second core solution was to gain a minimum floor space for the whole flexible assembly system. By adjusting the assembly postures of multiple components, projecting all the locating features on the base plane, different 2D convex hulls that formed by the projection results were built. With optimal combination operations, a minimum square summation of these convex hulls can be gained. Correspondingly, the motion stroke of the whole assembly system was designed optimally. Flexible design for assembling four different wing flap components was optimized to verify the methodology's feasibility. With the designed motion stroke, the flexible assembly system has a compact/simplified structure, and a sufficient assembly operation space, demonstrating a good locating/assembly performance. For the inclined spar part, the optimized average assembly deformation error is 0.071mm, which is consistent with practical assembly site.

Keywords: Flexible Tooling, Motion Stroke, Assembly Loads and Deformation, Structural Optimization.

1. Introduction

For aviation products, such as an aircraft, they require strict aerodynamic profile accuracy. Different from general mechanical products, it needs to ensure the structure shape/size, and meet the requirements of (1) design accuracy and (2) interchangeable consistency among different assemblies for an aircraft. As a result, the assembly work of aircraft needs the assistance of a large number of special locating devices [1]. Assembly tooling is used to support different components while they are being worked on, and to locate different parts together in the correct relative positions in the defined coordinate system.

To fit the requirements of ever-changing market, the development of flexible assembly tooling technology has been a focal point of investigation for aviation industry, because of the cost and time effectiveness. It's configuration can be adjusted to fit the changes of different assembly environments and assist the assembly with different shapes and sizes, and the accurate dimensional size/shape/spatial and assembly precision can be gained [2]. How to realize optimal design of flexible assembly tooling, such as layout relationship for different locating units, and motion stroke along each motion axis, are crucial problems.

The application of flexible assembly system has been paid much attention. Lu et al. [3] addressed a flexible system for machining the large-scale and thin-walled workpiece with vacuum suction cup units, and it also can be used for assembling different skin panels. Considering multiple constraints, Tadic et al. [4] proposed a general model for locating and clamping workpieces with complex geometry by two skewed holes to reduce the dependence on assembly tooling. For a better assembly flexibility, Erdem et al. [5] proposed an automated flexible assembly tooling for wing box assembly with force-controlled adjustments, and the tooling of hexapod solutions was taken as an enabler in the assembly process for cross sections. Jamshidi et al. [6] presented a rapid configuration for box-joint assembly jigs, the system was used on Airbus A380 subassembly, and the corresponding methodology for high accuracy installation of sustainable fixtures was also proposed.

For the general design and optimization methods relevant with flexible assembly tooling, Rabbani et al. [7] developed a comprehensive quadratic assignment problem for an integrated layout design of final assembly line, where genetic algorithm (GA) as well as memetic algorithm (MA) were proposed and implemented on different numerical examples. For sheet metal parts, Paramasivam et al. [8] developed an optimum design solution of jigs/fixtures with digraph and matrix methods, which was a simple and efficient methodology as selecting the optimum jig. For the fixture layout design, in order to locate thin-walled structures stably and accurately, Zhou et al. [9] presented a rapid design method for fixture layout based on hybrid particle swarm optimization (HPSO) algorithm, with regard of elastic plate theory, and the designed fixture layout had simply supported edges. Krishnakumar et al. [10] developed algorithms for designing the fixture layout with the help of FEM simulation to minimize workpiece deformation. With the static analysis of workpiece, Vasundara et al. [11] proposed a fixture layout system for drilling operation using RSM and ACA, the main focus is to predict fixture layout, and it can minimize the elastic deformation.

With the above analysis, for the assembly hierarchies of components and subassemblies, during their flexibility realization process, the practical assembly constraint conditions would bring more challenges as designing the flexible assembly tooling system, such as narrow assembly operating room, multi posture adjustment and assembly loads, complex assembly procedure, and so on. In this paper, with the purpose of realizing the optimal design of flexible assembly tooling, the motion stroke design of different locating units for multiple aircraft components is presented.

2. Motion stroke optimization of flexible assembly tooling

For the multiple flexible locators with a high flexibility, in order to optimize the structure layout and motion stroke, one optimum design process is proposed, as shown in Figure 1. In order to have a better understanding on this procedure, one statement is made here firstly. For the optional positioning area of multiple components, there often is a small difference for the height along the Z direction, due to the easy operation. And the motion stroke in the Z direction also has a small influence on the floor area of the whole tooling system. As a result, the optimization procedure is mainly based on the X/Y direction on the base plane XOY. Of course, taking the two main factors into account, i.e. the product posture and spatial position relationship of multiple components, this proposed method is also suitable for designing the motion stroke of Z direction.

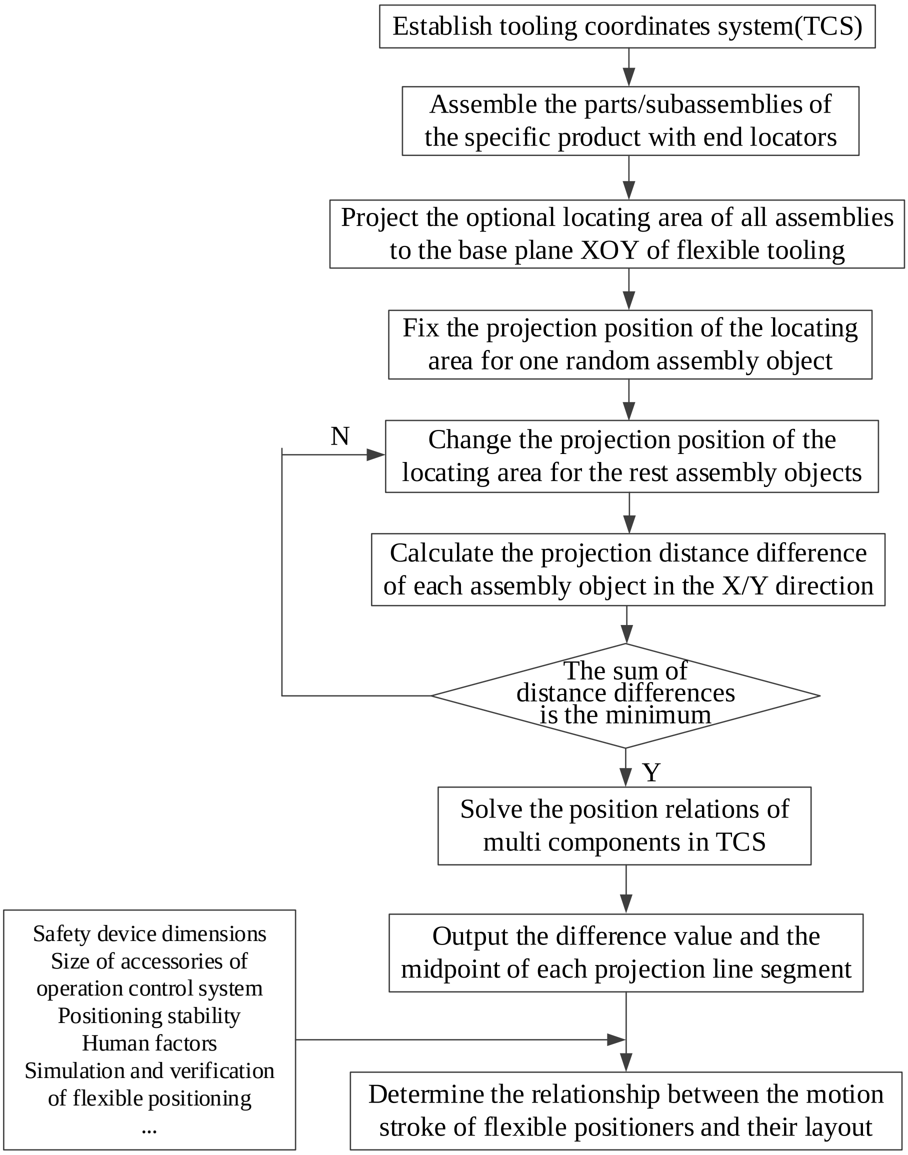


Figure 1 – Motion stroke and layout optimization process of flexible locators

Step 1: establish tooling coordinates system (TCS). The TCS is established within the basic framework of the entire flexible assembly tooling, according to three tooling ball (TB) points distributing on the corner, with the assistance of laser tracker.

Step 2: assemble the parts/subassemblies of the specific product with the end locating effectors. The end locators and the product to be assembled should have a correct correspondence relationship with each other. This operation is mainly carried out in the CATIA virtual assembly environment, with the analysis on the assembly posture adjustment of multiple assembly objects in the flexible assembly tooling. After the assembly posture is determined, (1) the structure of each locating feature and their relative spatial position distributing on different products, and (2) the similarity and difference for each geometric feature can be obtained directly. And it is also the previous step for cluster analysis and grouping optimization of product initial optional features.

It is mentioned that the initial optional features of the flexible tooling system are mainly determined by the structure, position distribution, and number of key product locating features. As well known, one typical characteristic for aviation parts is their weak rigidity, and it is easy to deform in the locating process. For parts with thin-walled structure, the special locating layout planning scheme, i.e. N+2+1(N⩾3) principle, is often used with the purpose of limiting their deformation [12]. The core problem in the over constrained locating scheme, is to determine the number and distribution of the locating points reasonably with a minimum deformation. For solving this question, an optimal method with the combination of finite element analysis and intelligent optimization algorithm is taken into account. However, the above method has the disadvantages of the calculation cost and efficiency. In this paper, the number N is divided into two portions, i.e. $N= N_1+ N_2$. Where N_1 is determined by the actual limitations of the product features, as mentioned in Section 4. For example, given there are four groups of key product characteristics, i.e. four hinge joints distributing on one beam, then the number of locating features of the assembly tooling is at least 4, i.e. $N_1 \geqslant 4$. For N_2, it is the other positioning points for limiting assembly deformation. As a design variable, N_2 is also obtained with the optimization solution under the number and position of constraint of N_1. The above searching process for N_2 can be modeled in Equation 1.

$$\begin{cases} Find\ X = [x_{N1,1}, x_{N1,2}, \cdots, x_{N1,i}, x_{N2,j}, x_{N2,k}, \cdots, x_{N2,n}] \\ \min f(X) = \sum_{i=1}^{k} U_i(X)/k \\ s.t.\ \ x_i \in \Omega \\ \qquad x_i \neq x_j \\ \qquad U_i(X)_{\max} \leq \overline{U_i(X)} \end{cases} \tag{1}$$

Where Ω stands for the feasible location area of the locating points that distributing on the product part. For different points, such as x_i and x_j, their position should not coincide with each other. U_i represents the deformation results of the k key measurement features for the given part, $\overline{U_i(X)}$ represents the required range of assembly deformation, and $f(X)$ represents the objective function relevant with N_2, i.e. the average assembly deformation value.

For the solution method based on the combination of intelligent optimization algorithm and finite element analysis, seven main steps are contained, i.e. (1) finite element modeling, (2) initial positioning layout planning, (3) constraint conditions defining, (4) parameter initialization for intelligent optimization algorithm, (5) the maximum and average deformation calculating, (6) change and evaluate the position of locating points, (7) output the optimized number/position of locating points. And their relationship can be shown in Figure 2. With this solution, the detailed locating area of all assemblies can be determined for designing the layout of the flexible assembly system accurately.

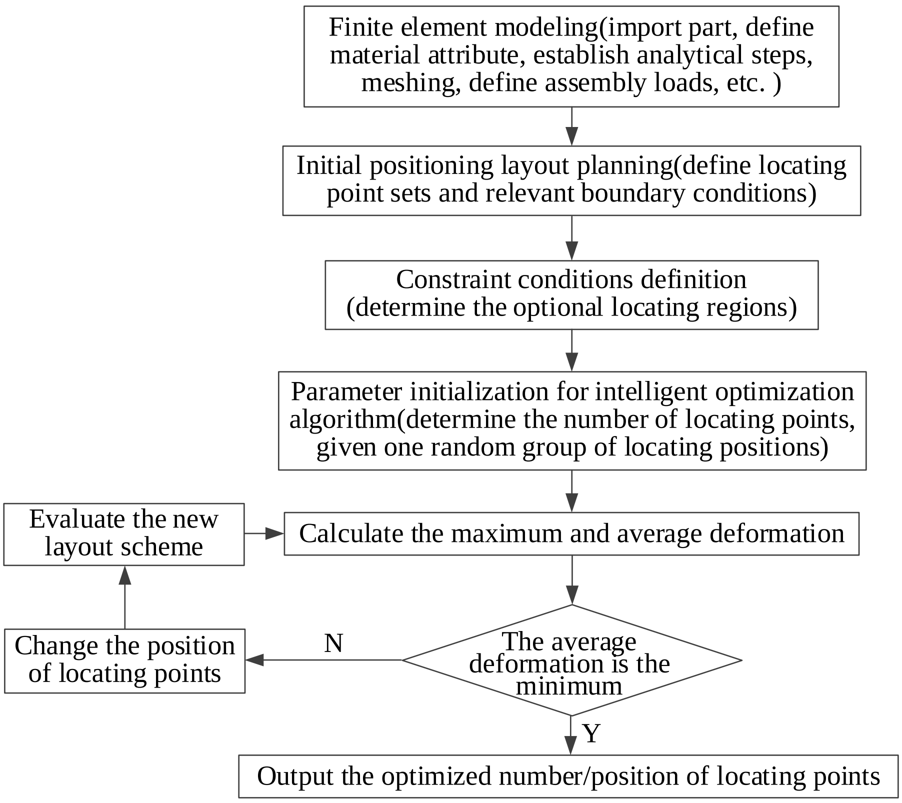


Figure 2 – Solution method for determining locating points for parts with a weak rigidity

Step 3: project the locating area of all assemblies to the base plane-*XOY* of tooling system.

For the process of multiple components assembly, the adjustment of product posture should be taken into account. As shown in Figure 3, $O_C\text{-}X_CY_CZ_C$ stands for the coordinate reference system of the current component to be assembled, and $O_T\text{-}X_TY_TZ_T$ stands for the coordinate reference system of the flexible assembly tooling.

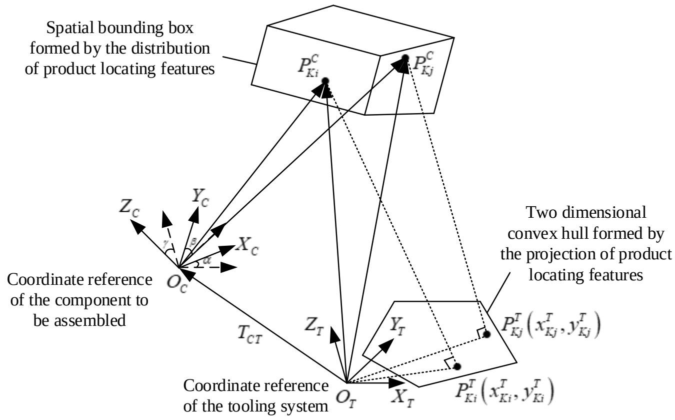


Figure 3 – Transformation from spatial bounding box to two-dimensional convex hull by projection

With a given random assembly posture in O_C-$X_CY_CZ_C$, because the geometric features of the subassemblies are complicated, and the plane or the curved surface is often taken as the locating datum in the assembly process, the above key locating features would form a positioning area. For the geometric features of the key characteristics, the variation of their distributing range would form a 3D point set, i.e. a spatial bounding box, and they also can be taken as a special positioning area. With the combination of the new projection points distributing on base the plane-$X_TO_TY_T$ of tooling system, a two dimensional convex hull would be formed by the projection results. The convex hull covers all of the projection points, and it can be solved by the *Convex Hull*( ) function module within the MATLAB software, where the graham scanning method is used [13]. After projecting the entire key characteristic distributing on the optional locating area to the base plane-*XOY*, their relevant regions would be converted to many two dimensional polygons. As shown in Figure 4, the vertical projections of six optional locating regions, i.e. P_1, P_2,⋯, P_6, for three products, i.e. *A*, *B*, and *C*, have different shapes and sizes. These 18 projection regions are closely related with the six flexible locators. The working range of each locator should cover the locating regions of the six components.

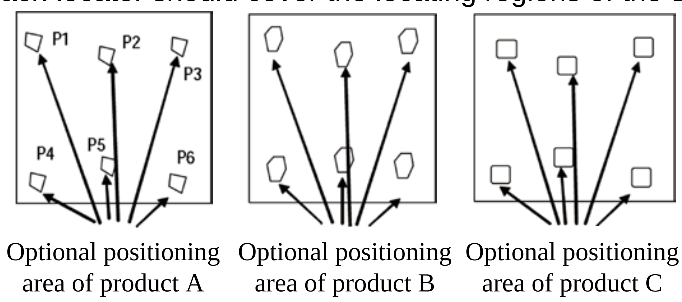


Figure 4 – Projection of the optional locating area of all assemblies on the base plane

Step 4: fix the projection position of the locating area for one random assembly object.

After the position of one random component is fixed on the base plane-*XOY*, then the fixed component can be taken as the layout datum, such as component *A* in Figure 4.

Step 5: change the projection position of the locating area for the rest assembly objects.

In this step, in order to change the projection position, the detailed solution is to move each component close to the fixed datum component. Given there are *m* components to be assembled on one flexible assembly system, and the components are denoted by C_i, $i=1, 2, \cdots, m$. The optional positioning regions of the i^{th} component are represented by C_{ij}, $j=1, 2, \cdots, n$. With the analysis in Step 3, it can be concluded that there should be *j* locating units for the whole flexible assembly system, i.e. L_j, $j=1, 2, \cdots, n$. With the position adjustment of the other components, the ranges of optional positioning regions are also going to change. And the motion stroke of each locating unit, should also meet the position differential requirement of the similar geometric features that distributing on different components.

As shown in Figure 5, with the projection operation, there are overlaps among the polygons of each C_{ij}. The phenomenon that there is interference area among each S_j happened. Where S_j represents the combined projection regions of C_{ij}. To divide them, firstly, move other components close to the fixed datum component along the *X* and *Y* directions. Secondly, observe the layout relationship among each red wireframe. The wireframe stands for the projection region, whose size is determined by the position change of each C_i. And the size also has a direct influence on the motion stroke of locating unit. Make sure the new combined projection regions, i.e. S_j', $j=1, 2, \cdots, n$, don't interfere with each other, at least.

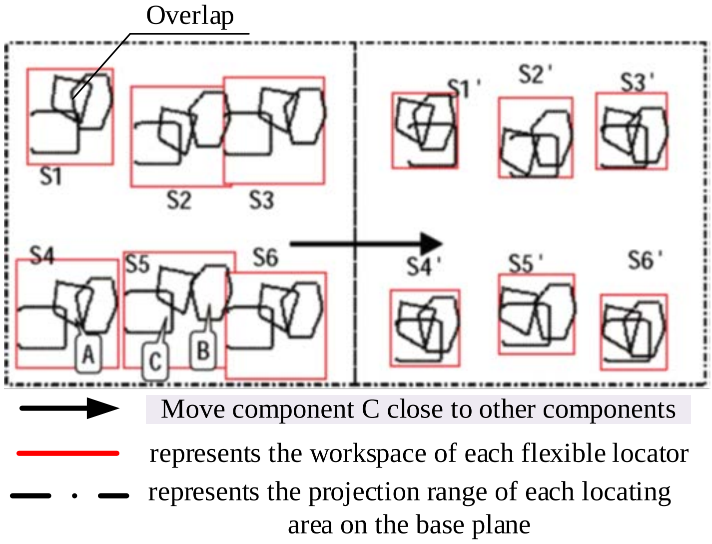


Figure 5 – Combination of the optional locating regions of all assemblies

Step 6: calculate the projection distance difference of each assembly object along X and Y directions.

With the recording of the changed position of each positioning region, the projection distance difference of each assembly object can be calculated. Given the original position of the j^{th} geometric feature for the datum component are $P_{1,j,x}$ and $P_{1,j,y}$ along the X and Y axis, respectively. The changed position of the j^{th} geometric feature for another assembly object, for example the i^{th} component, are $P_{i,j,x}$ and $P_{i,j,y}$ along the X and Y axis, respectively. With the math modeling, the motion stroke S_j of the j^{th} locating unit can be expressed with Equation 5. Where P_{ij} stands for the position of each positioning feature or region, and $i \neq 1$.

$$\begin{cases} S_{j,x} \geq \max(P_{i,j,x} - P_{1,j,x}) \\ S_{j,y} \geq \max(P_{i,j,y} - P_{1,j,y}) \end{cases} \tag{2}$$

Step 7: calculate the minimum sum of the distance differences.

To obtain the minimum motion stroke of each axis for the whole flexible tooling system, one efficient solution is to sum all of the projection distance difference for all components in the X and Y direction.

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\min\left(P_{i,j,x} - P_{1,j,x}\right) + \sum_{i=1}^{m}\sum_{j=1}^{n}\min\left(P_{i,j,y} - P_{1,j,y}\right) \tag{3}$$

As modeling the minimum sum of the distance differences, there are a lot of practical constraints during the assembly process, and they must also be taken into consideration.

Step 8: solve the position relations of multiple components in TCS.

On the base plane of flexible tooling, according to the inherent characteristics of the component structure and the objective function, the genetic algorithm [44] is used to implement the process of tooling layout optimization. The core idea of genetic algorithm is to carry out the operations of population selection, crossover, mutation, and so on, according to the principle of evolution theory. With the iterative calculations, the optimal population can be obtained, i.e. the solution of the objective function. The most apparent characteristic of this algorithm is that the operation process is oriented to structural objects, and there is no requirement for function continuity and derivative feasibility in the entire process. What's more, the exact expression of the function mapping relationship is not required.

Step 9: output the difference value and the midpoint of each projection line segment.

According to the optimum position relationship among different components, the position and posture of the components would be adjusted in the CATIA virtual environment. After recording the changed positions, i.e. re $P'_{i,j,x}$ and $P'_{i,j,y}$, the difference value of the optional locating region on each component can be calculated with Equation 4.

$$\begin{cases} \Delta d_{i,j,x} = P'_{i,j,x} - P_{1,j,x} \\ \Delta d_{i,j,y} = P'_{i,j,y} - P_{1,j,y} \end{cases} \quad (4)$$

Then the position of the midpoint for each projection line segment can be gained.

$$\begin{cases} m_{i,j,x} = \Delta d_{i,j,x} / 2 + P_{1,j,x} \\ m_{i,j,y} = \Delta d_{i,j,y} / 2 + P_{1,j,y} \end{cases} \quad (5)$$

Step 10: take other factors into account.

Considering the structural dimensions of the components and the locating units, the assembly simulation work of the multiple components and the flexible assembly system should be carried out under the DELMIA environment. With the check on (1) the motion stroke along each direction, and (2) the interference situations during the assembly process, the reach-ability of flexible positioning device and the feasibility of reconfiguration are verified. What's more, the flexible assembly path can be determined through simulation feedback. The motion stroke of each positioning direction and the spatial layout relationship among each locating unit would be amended. In addition, the correlation analysis between the tooling and the target component can be realized, and the data set required by the positioning control system is gained.

Step 11: determine the motion stroke of each flexible locating unit and their layout.

With step 9 and step 10, the optimization work has been done. Because the combination of the optional locating regions of all assemblies have a direct relationship with each locating units, the difference value $\Delta d_{i,j}$ can be taken as the motion stroke of each locating unit, and the midpoint of each projection line segment can be taken as the position of each unit on the base plane of the tooling system. With this operation, the detailed design work on layout planning can be finished for the whole flexible assembly system.

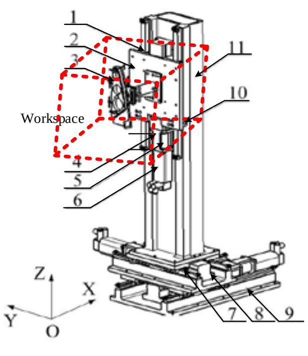
3. Experiment verification

3.1 Structure of the locating unit of the flexible assembly system

As shown in Figure 6. In this paper, the locating unit with three motion layers is taken as the research object. The locating unit can accomplish the movement of three liner directions, i.e. *X*, *Y*, and *Z*. Each motion direction is composed by servo drive system, high-precision guiding system with certain preloading force, and ball screw drive system, and so on. The locating unit is used for assembly the wing flap components. The main parts of the component are separated as ribs, beam(s), hinge joints, skin panel etc.

3.2 Motion stroke optimization of flexible assembly tooling

With the consideration of designing locating scheme based on practical constraint conditions, it is known that the accurate position of detailed locating features for ribs, hinge joints, skin panel, etc. can be determined easily. However, for the beam part, it is a long and narrow part, due to the weak rigidity, the locating deformation is unavoidable.



1. Guiding rail;2. Connecting plate;3.End locating effecter ;4. Connecting flange;5. Shaft coupling;6. Servo motor;

7. Ball screw;8. Bearing seat;9. Column base;10. Pneumatic clamping parts;11. Column body

Figure 6 – Flexible locating unit and its locating range

For one kind of beam, its main structural parameters are presented as follows. The thickness is

2 mm, the length is about 2 m, the width is about from 230 mm to 120 mm, and its structural view is shown in Figure 7. For the assembly loads, the drilling force and the gravity is mainly considered. At the position of two end ribs 1# and 14#, and the both sides of central ribs 7# and 8#, the drilling force is distributed on the entire width direction of the beam. Considering the assembly of the beam and trailing edge panel of this flap component, the drilling force is also distributing on the upper area of the beam, as shown by the side view.

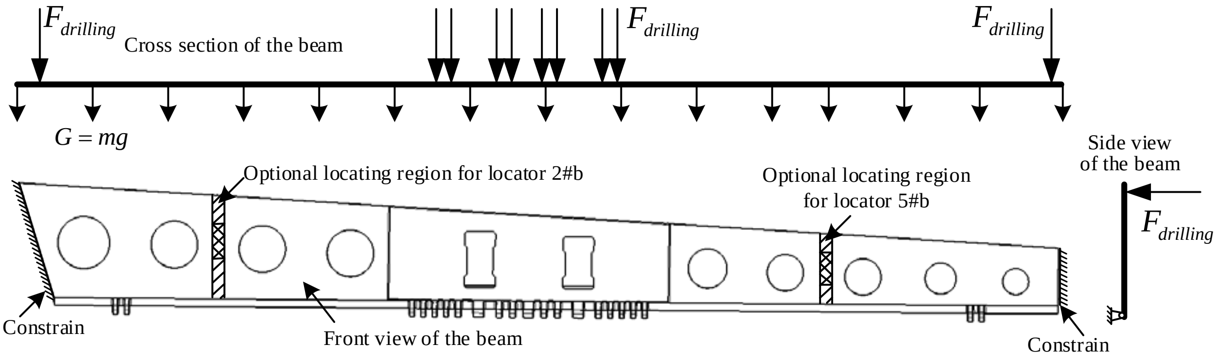


Figure 7 – Assembly loads and constraints of the inner beam

Considering the specific assembly process parameters, it is found that the drilling force is 107 N. In addition, the gravity is also one of the external loads, and it distributes evenly along the entire beam part. For the assembly constraints, the hinge joints are located by the end locators, and the movement freedom of the beam along y and z direction is limited. But the beam could still rotate around the hole axis. It is mentioned that the above constraint is taken as a fixed hinge constraint. In addition, the two end side faces of the beam are blocked by the locators of tooling unit 1# and 6#, respectively. And the above two constraints limit the movement degree along the x axis and the rotation degree along the y and z axis. In conclusion, the above key features of the beam can be taken as the locating set, i.e. N1.

For the locating set N2, it has a function of limiting assembly deformation. With the analysis on (1) flexible assembly process and group optimization of product locating features, and (2) mapping relationship between product locating features and flexible tooling features that presented in this section, it can be known that the number of locators is two, i.e. 2#b and 5#b. While, for the position of the two specific locators, they can’t be changed along the x direction, due to the limitation of mechanical structure of tooling unit 2# and 4#. As a result, the shape of their optional locating region would form a banded area, as shown by the shadow region in Figure 7. In order to (1) minimize the locating deformation of the web surface along the beam’s normal direction, and (2) determine the y/z motion stroke of the locators 2# and 5# accurately, the two locating positions should be optimized, i.e. the accurate position of N2 that distributing within the above banded area.

Due to the structure differences, for the beam of the outboard component, its main structural parameters are presented as follows. The thickness is also 2 mm, the length of the first section is about 1.1 m, the second length is about 700 mm, the width is about from 120 mm to 70 mm, and to 30 mm at the end, as shown in the Figure 17. The drilling force is distributed at the position of ribs 15#, 27#, 20# and 21#. Considering the assembly of the beam and trailing edge panel of this component, the drilling force is also distributing on the upper area of the beam. Due to the beam is comprised of two sections and more hinge joints, the locating set N1 is different from the inboard component, and the initial number of locators is three, i.e. 2#b, 4#a, and 5#b. Consequently, three locating positions should be optimized.

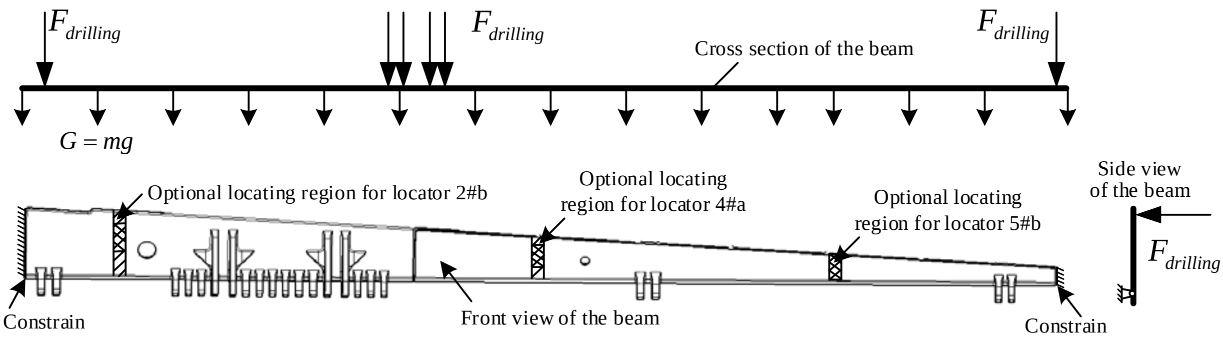


Figure 8 – Assembly loads and constraints of the outer beam

To determine the accurate locating regions and reduce the assembly deformation considering practical assembly constraints, relevant optimization work is done. For the finite element simulation calculation, the lattice unit is divided by shell unit S4R, and the elastic contactless model is adopted. Then with iterative calculation, it is found that the optimized locating regions for the above two beams, can be shown by the grid area, as already presented in Figure 7 and 8. For this locating scheme, the maximum assembly deformation is 0.0908mm, and the minimum deformation is 0.0513mm. Then a conclusion can be gained, i.e. this locating scheme can fit the design requirement well.

With the optimized locating regions for each parts, to obtain the optimum structure layout relationship, and the minimum motion of all the seven locating units, for the practical optimal design process, relevant parameters of the genetic algorithm are shown in Table 1.

Table 1 – Calculation parameters of genetic optimization algorithm

Number of iterations	Population number	Numerical length	Crossover rate	Mutation rate	Population interval
200	180	6	0.2	0.1	1

According to the above detailed constraints, with the assembly simulation operations under DELMIA environment, the overall layout relationship among seven locating units of the flexible tooling system is determined, as shown in Figure 9. It can be known the layout scheme of the flexible assembly tooling is comprised by three rows, and they are parallel to each other. Then for the layout relationship along x axis, the position of these locating units is mainly determined by the distribution differences of relevant product features. From the overall point of view, although the whole assembly system has a very compact structure, the locating function can be realized well, and the assembly operating space is sufficient with the verification of assembly simulation.

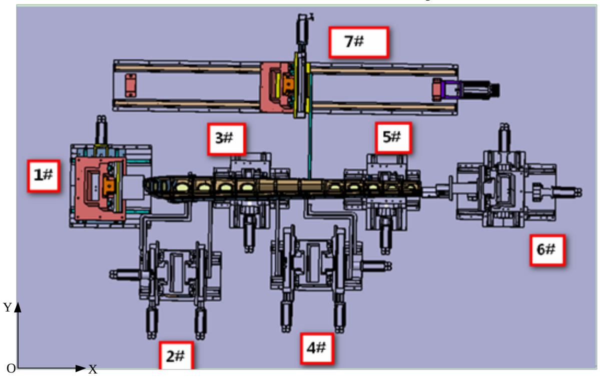


Figure 9 – Layout relationship among the locating units of the flexible tooling system

With the above optimization operations, the motion stroke of each locating unit along *x*, *y*, and *z* axis of the flexible assembly tooling system are obtained, as shown in Table 2. The tooling system works well in practical assembly site, the assembly operation space is relatively spacious, and the assembly precision can satisfy the design requiremen.

Table 2 – Optimized motion stroke of each locating unit

	1#（mm）	2#（mm）	3#（mm）	4#（mm）	5#（mm）	6#（mm）	7#（mm）
x-axis	165	120	100	200	100	300	1850
y-axis	150	180	150	200	150	150	200
z-axis	200	200	120	200	120	200	500

4. Conclusions

With the constraints of assembly operation space, assembly constraints (such as assembly loads, locating freedom constraint, etc.), product posture and other specific assembly characteristic, a design procedure with eleven steps is proposed and modeled.

The flexible assembly system has a compact/simplified tooling structure and a sufficient assembly operation space. With iterative virtual simulation and intelligent computing, the production area and tooling manufacturing cost is reduced.

5. Acknowledgments

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