Optimization of the number and positions of fixture locators for curved thin-walled parts by whale optimization algorithm

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Abstract. Optimizing the fixture layout of the locating element is an important method to reduce the clamping deformation of thin-walled parts. A method for optimizing the fixture layout based on whale optimization algorithm is proposed in this paper, the number and positions of the fixtures for curved thin-walled parts are optimized. Firstly, the multi-point flexible locating tooling for curved thin-walled parts is developed based on the multi-point support technology. Then the strain energy is used to describe the deformation of the curved thin-walled parts in all directions, and an optimization model that takes the position of the locating element as a decision variable and minimum strain energy as the goal is established. Combined with the whale optimization algorithm and the parameterized finite element analysis, the optimal design of the number and positions of fixture locators for curved thin-walled parts are realized. Finally, the effectiveness of the proposed method is validated by the aircraft skin locating layout optimization, and a multi-point flexible locating and deformation measurement platform is constructed to verify the results of finite element calculations.

1. Introduction

The widespread use of thin-walled structural parts is an inevitable trend in aircraft manufacturing due to their light weight, high strength, and smooth geometric modeling. However, the typical thin-walled structural parts are mostly large-sized and weakly rigid, which make them always tend to deform even when only subjected to gravity. Clamping is an important factor affecting the deformation of thin-walled parts. An unreasonable clamping scheme will cause unacceptable deformation and affect the assembly quality [1]. As shown in Figure 1, Cai [2] first proposed the “N-2-1” locating principle for weak rigid thin-walled parts, N (N>3) locators are used on the primary datum plane to limit the deformation of thin-walled parts by over-locating.

As is known, the increase in locators will inevitably lead to the increase in time and cost, besides, the manufacturing deviation and the locating deviation in the clamping process will have more complicated effects on the final deformation, which determine that the value of “N” should as small as possible. Therefore, the locating layout optimization of thin-walled parts is to find the smallest number of “N” that meets the requirements of assembly accuracy, and then optimize the positions of locators to minimize the deformation. The primary problem faced by the fixture designer is how to determine the optimal number and positions of locating elements.
In order to solve the problem, many scholars have carried out a lot of research. Combining finite element analysis to calculate deformation and intelligent optimization algorithm to optimize the position under a given number is the mainstream method. Based on the ant colony algorithm, Padmanaban et al. [3] minimizing the elastic deformation of the workpiece during the machining process by optimized the fixture layout. Shi et al. [4] developed an optimization method for locating points based on genetic algorithm using APDL language, and studied the distribution of locating points under gravity. Cheng et al. [5] established a hierarchical locating layout optimization model for the automatic drilling and riveting process of aviation thin-walled parts, and combined genetic algorithm and ant colony algorithm to optimize the locating point position. Zhang et al. [6] proposed an improved particle swarm algorithm based on inertia weight, and applied the optimization algorithm to the optimal design of fixtures. To minimize the average deformation, Yu et al. [7] optimized the clamping position in the milling of thin-walled parts based on genetic algorithm. Zhou et al. [8] combined finite element analysis and ant colony genetic hybrid algorithm to optimize the layout of the support array, which reduced the maximum deformation of thin-walled parts by 47%. Aimed to minimize the maximum deformation caused by the self-weight of the workpiece, Wang et al. [9] used the firefly algorithm to achieve the iterative optimization of the locating layout.

This paper proposes a new method to the optimization of the number and the positions of fixture locators for curved thin-walled parts. First, the multi-point flexible locating tooling for curved thin-walled parts is developed, then the strain energy is used to measure the deformation in all directions for free-form thin-walled parts, and the number and positions of fixtures are optimized by combining whale optimization algorithm and finite element analysis. Finally, the proposed method is verified by taking aircraft skin fixture layout optimization as an example and the experimental locating deformation is compared to those determined from the finite element analysis.

2. Multi-point locating tooling

For the locating of curved thin-walled parts, the multi-point flexible locating method with a higher degree of conformity to the inner surface is often used. The multi-point locating tooling is a tooling that discretizes the support area into multiple support points, and the spatial position of each support point can be adjusted independently.

The core of the multi-point flexible locating tooling is to adjust the distribution of the flexible support dot matrix to generate a support surface consistent with the shape of the locating surface. The structure of the multi-point flexible locating tooling used in this paper is shown in Figure 2, which is mainly composed of work platform, X-direction guide rails, Y-direction sliders and Z-direction locating telescopic columns, locating ball heads, and hand driving wheels. The four X-direction guide rails can move along the X-direction through T-shaped guide grooves on the work platform. On each guide rail, there are four sliding blocks that can slide in the Y direction, and each sliding block is fixed with a Z-direction locating telescopic column. All the transmissions in the system are driven manually, which can be directly pushed in the X and Y directions, while in the Z direction, the worm gear transmission scheme is used to convert the rotation of the hand wheel into the movement of the locating ball in the Z direction. In this way, the locating ball head can theoretically be located at any spatial position, and with the aid of a laser tracker, the locating ball head can be adjusted to generate a supporting surface.
consistent with the shape of the curved surface of the thin-walled part to be located.

Figure 2. Structure of the multi-point flexible locating tooling

3. Optimization model

3.1 Strain energy
Elastic strain energy refers to the energy stored in the workpiece due to elastic deformation, also called deformation energy. As shown in Figure 3, for a three-dimensional linear elastic body, it can be considered to be composed of many small cube elements. Under the action of load $F$, elastic deformation $D$ is produced, which generates stress inside each element body.

Express stress and strain in the form of vectors, we can get:

\[
\{\sigma\}^T = \left\{\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz}\right\}
\]

\[
\{\varepsilon\}^T = \left\{\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{xz}, \gamma_{yz}\right\}
\]

So the total strain energy can be described as:

\[
U = \frac{1}{2} \left\{\sigma\right\}^T \{\varepsilon\} dV
\]

Under different locating layouts, thin-walled parts will produce different deformations subjected to the gravity or other assembly loads. However, these are all stored in the thin-walled parts in the form of strain energy. Therefore, strain energy is a good indicator to measure the overall degree of deformation.

3.2 Fixture layout optimization model
As the deformation of thin-walled parts is proportional to the overall strain energy, the strain energy can be used to measure the deformation. That is, the smaller the deformation, the smaller the overall strain energy. Therefore, minimizing the deformation of thin-walled parts can be converted to minimizing the overall strain energy. Taking the positions of locating points on the main locating surface as a design variable, fixture layout optimization problem is formulated as follows:
Among them, M represents the number of locating points under each layout, \( U_i \) represents the strain energy of each finite element, \( K \) is the number of elements in the finite element model, and \( f(X) \) is the objective function, which represents the total strain energy of \( K \) elements in the finite element model under each layout. The constraint condition is that each locating point must be within the effective range \( \Omega \) allowed by the workpiece, and the positions of different locating points cannot overlap.

4. Optimization strategy

4.1 Whale optimization algorithm

Inspired by the bubble-net hunting strategy, Mirjalili et al. \cite{10} proposed a new meta-heuristic swarm intelligence optimization algorithm—Whale optimization algorithm (WOA) in 2016. The algorithm simulates the behavior of Humpback Whales in their search for food and migration, and has the advantages of fewer adjustment parameters, strong optimization ability, and simple implementation.

WOA is inspired by the unique hunting mechanism of humpback whales in nature. Humpback whales hunt small fish or krill near the surface. When they find prey, they first dive to a depth of about twelve meters, then spiral to the surface. WOA modeled mathematically the three behaviors of humpback whales in the hunting process, namely, prey encircling, bubble-net attacking and prey search. Research has shown that whale optimization algorithm has better performance compared with particle swarm optimization and ant colony algorithm \cite{11}. The pseudo code of this algorithm applied to the fixture layout optimization of thin-walled parts is as follows:

The pseudo-code of WOA

Define objective function \( f(X) \)
Initialize \( n \) sets of fixture layout solutions \( X_i \) (\( i=1,...,n \))
Calculate the fitness values of each search agent
Find the optimal solution \( X^* \) in the initial layout
while (\( t < \) Number of iterations)
for \( i=1:n \)
Update parameters
If1 (\( p < 0.5 \))
If2 (\( |A| < 1 \))
Update the position of the current search agent by the \( X(t+1) = X^* - A \cdot D \)
\( D = (C \cdot X^*(t) - X(t)) \), \( A = 2a \cdot r - a \), \( C = 2\cdot r \), where \( a \) is linearly decreased from 2 to 0 over the course of iterations, and \( r \) is a random number in [0,1]
Else If2 (\( |A| > 1 \))
Select a random search agent (\( X_r \))
Update the position of the current search agent by \( X(t+1) = X_r - A \cdot D \)
End if2
Else If1 (\( p > 0.5 \))
Update the position of the current search agent by
\( X(t+1) = D \cdot e^{i\cdot \cos(2\pi \cdot j)} \cdot X^*(t) \)
Where \( k \) is a constant for defining the shape of the logarithmic spiral, and \( j \) is a random number in [-1,1]
End if1
End for
Check if any search agent goes beyond the search space and amend it
Calculate the fitness of each search agent
Update $X^*$ if there is a better solution
$t = t + 1$
End while
Return $X^*$

4.2 Determination of the optimal number
From the above analysis, it can be known that the value of “N” should be as small as possible under the premise of ensuring that the assembly deformation is not out of tolerance, and the maximum deformation of the thin-walled part can be significantly reduced if the locating element can be applied to the node with relatively large deformation. Therefore, the following strategy to determine the optimal number of locating points is adopted: First, according to the “3-2-1” locating criterion, three points on the primary datum plane are used for position constraints and the deformation of thin-walled parts under its own weight are calculated. Then, one locating element is added to the node with the largest deformation, and the deformation of the thin-walled part with new boundary conditions is calculated again, and add another locating element to the node with the largest deformation at this time. Continue this process until the assembly accuracy requirements of the workpiece are met. Finally, the initial number and position of locating elements can be determined in this way.

The optimization of the locating layout is based on the initial layout. If there are “Ns” locating points in the initial layout, the first step of the optimization process is to remove the last added locating points and optimize the positions of the reserved “Ns-1” points. If the assembly accuracy requirements can be met after the “Ns-1” locating points are optimized, remove the last added locating point among the “Ns-1” locating points, and optimize the reserved “Ns-2” points. The process continues until the minimum number of locating points is used to meet the assembly accuracy requirements. After determining the optimal number of locating points, optimizing the positions of the locating points can obtain a locating layout with the optimal number and positions. The process for obtaining the optimal number of locating points using the above strategy is shown in Figure 4:

![Flowchart for optimizing the number of locating points](image)

**Figure 4. Flowchart for optimizing the number of locating points**

4.3 Optimization of fixture location
By combining the whale optimization algorithm with finite element analysis, the whale optimization algorithm is used as the optimization program in the MATLAB environment to search the optimal solution, and the finite element software ABAQUS is used to numerically calculate the strain...
energy(ALLSE), the optimal fixture layout is determined by searching the optimal variables to control
the overall assembly deformation. The main steps of the optimization process are as follows:

**Step 1 Initialize the layout.** Based on the establishment of the optimal number of locators, the initial
position under the optimal number in the feasible region is randomly generated by Latin hypercube
sampling.

**Step 2 Parametric finite element analysis.** The parameterized finite element model and
post-processing process are established through the secondary development of ABAQUS software
based on Python language. In this way, the position of the anchor point can be changed continuously; a
large number of loop iterative calculations can be performed efficiently.

**Step 3 Joint Computing.** Call the Python script file in the MATLAB operating environment to
update the population information (i.e., the positions of the locators), and use the batch command to call
the script file to perform finite element analysis in the background. After the analysis is completed, the
result file is read and the fitness value is assigned to the corresponding population.

**Step 4 Iterative Optimization.** Evaluate the fitness value of the initial population, find the optimal
and update the positions through the WOA, repeat step 3 to generate a new solution. If the new solution
is better, accept the new one, and iterate in this way until the global optimal solution is obtained.

The fixture locating layout optimization process is shown in Figure 5.

![Figure 5](image1.png)

**Figure 5.** Process of fixture locating layout optimization based on WOA

5. **Case study**

In this section, the process and effectiveness of the proposed method are illustrated by an aircraft skin
parts case. The fixture locating scheme of the case based on the “N-2-1” locating principle is shown in
Figure 6. The sheet metal has dimensions of $1700 \times 1150 \times 3$ mm$^3$ and the physical material properties are
listed in Table 1. The “N” locating points on the primary datum plane are $L_{f1}-L_{fn}$, on which the local
coordinate systems are built and the normal displacement constraints are applied respectively. The
second datum plane applies two Z-direction displacement constraints through the positioning points $L_{S1}$
and $L_{S2}$, and the third reference surface applies one X-direction displacement constraint through the
locating points $L_{t3}$. The allowable maximum deformation under its deadweight is set as 1 mm.
Figure 6. Finite element model of skin locating

On the two edges of the model, 170 and 120 meshes are divided respectively, and 20691 nodes and 20,400 elements are contained in the whole model. The element type is shell element S4R. The coordinates of the fixed locating points $L_{s1}$, $L_{s2}$ and $L_{t3}$ are set as $(50, 0)$, $(120, 0)$ and $(0, 60)$. The locating points to be optimized are $L_{f1}$, $L_{f2}$...$L_{fn}$, and their corresponding position coordinates are denoted by $(x_1, y_1)$, $(x_2, y_2)$, ..., $(x_n, y_n)$ respectively. The relationship between node number and position coordinates is as follows:

$$\text{Node}(i) = 121 \times x_n + y_n + 1 \quad (4)$$

Table 1. The physical properties of materials.

| Item             | Value         |
|------------------|---------------|
| Mass density     | $2.8 \times 10^{-3} \text{g/mm}^3$ |
| Young's modulus  | $7.3 \times 10^4 \text{MPa}$      |
| Poisson ratio    | 0.33          |

5.1 Optimization process

5.1.1 Optimization of number

Firstly, the optimal number of locating elements should be determined by the above method. The initial layout is applied due to the “3-2-1” principle; it is found that the maximum deformation value obtained by finite element calculation is 1.897 mm at the node number 17459. Therefore, add a locating point at the maximum deformation point for displacement constraint, continue to repeat the finite element analysis of the previous step, and the maximum clamping deformation at this time is 1.335, which still does not meet the assembly accuracy. Therefore, repeat the above steps until the number of used locators can meet the accuracy requirements. The calculation deformation results under different numbers are shown in Table 2.

Table 2. Clamping deformation under different numbers

| N     | Max deformation(mm) | Node number | ALLSE (mJ) |
|-------|---------------------|-------------|------------|
| initial | 1.897               | 17459       | 246.585    |
| N=4    | 1.335               | 7291        | 191.990    |
| N=5    | 1.116               | 19304       | 163.472    |
| N=6    | 0.883               | 10451       | 132.565    |

According to the numerical calculation results, when the value of N is 6, the accuracy requirements can be met, but whether this value is the smallest still needs to be further determined. For this, the locating points added at node 10451 are subtracted, only five locating points are used for displacement constraint and their positions should be optimized according to the optimization strategy.

Taking the minimum overall strain energy of the skin as the optimization goal, the position of the five locating points are optimized. Take the population size whale optimization algorithm as 20. The fitness convergence curve of five locators is shown in Figure 7. After 100 generations of iterative optimization, the overall strain energy of the thin-walled part at the optimal position is 149.792 mill joules, and the
maximum deformation is 1.0916 mm, which still not meet the accuracy requirement of assembly deformation. It can be seen that even under the optimal layout, the general engineering accuracy requirements still cannot be met with five locators. However, the required accuracy requirements can be met although the position is not optimized with six locators. So the optimal number of “N” is 6.

5.1.2 **Optimization of positions**

After determining the optimal number, its position under the optimal number can be optimized. So we take the position of the six locating points as the optimization variable, and the initial positions are randomly generated, and the positioning and layout optimization strategy based on the whale optimization algorithm is adopted to optimize the position of locators globally. Take the population size whale optimization algorithm as 20, and the number of iterations as 100 generations. The fitness convergence curve with six locators is shown in Figure 8.

![Figure 8. The fitness values with six locators](image)

It shows that when the number of iterations is about 30 generations, the curve has reached a state of convergence and tends to be stable, indicating that the whale optimization algorithm has good convergence performance. At the same time, arrange six locating points uniformly according to experience under the same condition to calculate the finite element analysis. The results of the empirical design and the optimized design are shown in Table 3.

| Empirical design | Optimized design |
|------------------|------------------|
| Max Deformation (mm) | 0.8767 | 0.6981 |
| ALLSE (mJ) | 149.169 | 109.598 |
| Node number | (5123,10121,15161,15201,10161,5163) | (2455,5505,10920,18181,17026,4941) |

As the result shows, compared with empirical design, the layout obtained by the proposed optimization strategy is much better, the strain energy is reduced by 20.3%, and the maximum deformation value is reduced by 26.5%. Under the optimized design layout, both the maximum
deformation value and the overall strain energy of the part is greatly reduced, indicating that the locating layout optimization method proposed in this paper can solve the problem of curved thin-walled parts scientifically and effectively, and the optimization results are superior to traditional empirical design.

5.2 Experiment test
In order to verify the correctness of the finite element model and the locating layout optimization results, a multi-point flexible locating and deformation measurement tooling for free-form thin-walled parts is developed based on the design scheme in section 1 to compare the clamping deformation obtained by the experiment and the finite element analysis under the optimal layout. Combined with Handy SCAN handheld laser scanner and laser tracker, the thin-walled multi-point flexible locating and deformation measurement test platform is built as shown in Figure 9.

![Figure 9. Multi-point flexible locating and deformation measurement platform](image)

Manufacture the aircraft fuselage wall panels with the same size as the finite element model, and scan the clamped part with the Handy SCAN 3D portable laser scanner to obtain the point cloud data. The accurate 3D digital model of the wall panel can be obtained by splicing the point cloud data with the assistance of 3D data detection software Geomagic Qualify. Then the clamping deformation can be obtained by comparing with the theoretical model before clamping.

![Figure 10. The deformation cloud map of the test part](image)

Figure 10 shows the deformation cloud diagram of the test part under the optimal layout. As the strain energy reflects the overall deformation of thin-walled parts, a total of 117 key measurement points in thirteen rows and nine columns are uniformly selected on the test part to compares the average clamping deformation between the experiment and the finite element analysis. The deformation comparison results at the key measurement points are shown in Figure 11.
At the selected key measurement points under the optimal layout, the average clamping deformation of the test part obtained by experiment is 0.243mm. At the same observation point, the average clamping deformation obtained by finite element analysis is 0.265mm; the average clamping deformation error is 9.1%. It can be considered that the clamping analysis model established in this paper is correct, and the locating layout optimization strategy based on the whale optimization algorithm can effectively solve the locating layout optimization problem of thin-walled parts.

6. Conclusion
A new fixture layout optimization method for thin-walled parts based on whale optimization algorithm is proposed in this paper. Combining finite element analysis and whale optimization algorithm, the overall strain energy of thin-walled parts is minimized by optimizing the number and positions of locating components. The main conclusions are drawn as follows:

(1) By computing the normal direction of the locating point on the free-form surface, a finite element model of the curved thin-walled parts under the normal constraints is established, which improves the accuracy of the model.

(2) Strain energy can reflect the elastic deformation of thin-walled parts in all directions, which is more suitable as an objective function for the fixture layout optimization problem of curved thin-walled parts.

(3) Combining finite element analysis with whale optimization algorithm, the proposed method can effectively solve the fixture layout optimization problem of curved thin-walled parts under the action of dead weight, and the optimization results meet the engineering requirements. It can be further applied to the condition under complex assembly loads such as hole making force and riveting force.

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