Tolerance analysis and optimization based on 3DCS

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Abstract. At present, with the increasing requirements of major enterprises on assembly accuracy, the problem of interference and excessive clearance between parts needs to be solved. In order to analyze and optimize the tolerances in the actual assembly of the parts, a three-dimensional vector ring model is proposed on the basis of the dimensional chain model, and the tolerance distribution is optimized by the "dichotomy method". With the help of 3DCS, the virtual assembly of the automobile headlight is carried out, and the sensitivity analysis is carried out by establishing the measurement of the gap between the turn signal and headlight in the automobile headlight, and the simulation results are used to obtain a reasonable improvement in tolerance allocation that meets the design criteria and saves costs. The results are compared with the traditional method of optimizing the allocation of equal tolerances and are clearly superior, providing a method for optimizing the allocation of tolerances to parts in engineering practice.

1. Introduction

Nowadays, people's requirements for mechanical products are gradually becoming more precise and complex, therefore, the study of mechanical product accuracy has become the mainstream direction of current scholars' research, and computer-aided tolerance analysis has become more and more popular. Traditional product quality testing is usually carried out using sampling methods, which is inefficient and the test results are contingent and not representative. Computer-aided tolerance assembly is a virtual assembly technology, that is, the assembly of each part in a virtual environment, the key technologies are modeling tolerances in the virtual environment, assembly accuracy prediction and optimization. At present, national and international scholars have conducted many studies in tolerance modeling and analysis. Peng and others [1] used the vector ring tolerance assembly model for two-dimensional dimensional chain tolerance analysis to calculate the sensitivity coefficient of closed-loop tolerance, which solved the problem that the function between the assembly response surface of the part and the design variables is difficult to obtain. Liu Zhuang [2] classified the assembly of parts from two directions, static and dynamic, and used VISVSA software to simulate and study the assembly order of parts, and achieved the minimization of assembly error by adjusting the assembly order of parts. Xu Xihui et al [3] similarly studied the importance of tolerance design in dimensional engineering and carried out tolerance modeling and analysis of automotive doors, wings and side surrounds with the help of 3DCS Measure as well as Move. Gao Lei et al [4] introduced the idea of parallelism to deal with the deviation transfer problem between part assemblies, introduced low deviation sequences into Monte Carlo methods, and finally optimized the tolerances based on fuzzy quality loss functions and manufacturing costs thus obtaining the tolerances of the constituent rings. Fan Manzhen et al [5] used the particle swarm method to assign the tolerances of automobile door assembly based on the cost-quality model and evaluated it by the quality cost theory to verify the reasonableness of the tolerance assignment. At
present, there are few methods to construct 3D dimensional chains for component assembly, and there is a lack of simple and feasible methods for tolerance optimization. Therefore, in this paper, after constructing a 3D dimensional vector ring model, a simple and feasible "dichotomy method" is used to analyze and optimize the tolerances with the help of 3DCS, which provides guidance for engineering practice.

2. Construction of 3D dimensional chain vector ring model

The tolerance information modeling technique starts from the design of the product model tolerance, and then to the analysis of the solution of the designed tolerance model, and finally the mathematical model of the dimensional chain of the tolerance model is obtained by vector representation. The key to tolerance information modelling is to convert the tolerance information model into a mathematical model for solving. The 3D dimensional chain vector ring is to represent the three-dimensional tolerance model with space vectors into a set of vector rings connected at the beginning and the end, and then project each constituent ring to the closed ring to convert the three-dimensional vectors into two-dimensional vectors to derive the general expression of the dimensional chain equation, the method converts the complex dimensional chain into a simple dimensional chain, and more convenient for the solution afterwards.

In the three-dimensional dimensional vector ring model, the mode of the constituent ring vector is the actual length of the dimension, and the direction of the constituent ring vector is the actual assembly direction of the part, as shown in figure 1. In the space-rectangular coordinate system, each constituent ring vector is denoted by \( \mathbf{L}_i \), constituent ring dimension is denoted by \( l_i \), the closed ring vector is denoted by \( \mathbf{L}_0 \), the closed ring dimension is denoted by \( l_0 \), and the angle between the constituent ring and the closed ring is \( \alpha_i \) .

![Figure 1. Three-dimensional vector ring model.](image)

In practice, the dimensions of the closed ring and each constituent ring will vary, and the variations are denoted by \( \Delta l_0 \), \( \Delta l_i \), where \( n \) denotes the number of rings of the constituent ring. Then the functional relationship between the closed ring and the constituent rings can be expressed as:

\[
l_0 + \Delta l_0 = h(l_1 + \Delta l_1, l_2 + \Delta l_2, \ldots, l_n + \Delta l_n)
\]  

(1)

Expanding the functional relationship between the closed and constituent rings using Taylor's formula and ignoring higher order terms:

\[
\Delta l_0 = \sum_{i=1}^{n} \frac{\partial h}{\partial l_i} \Delta l_i
\]  

(2)

Where \( \frac{\partial h}{\partial l_i} \) is the transfer coefficient, that is the extent to which the amount of dimensional change in the constituent rings affects the closed ring dimensions.

From the knowledge of vector theory, it is known that the relationship between the constituent and closed rings is:

\[
\mathbf{L}_0 = \mathbf{L}_1 + \mathbf{L}_2 + \cdots + \mathbf{L}_n
\]  

(3)

\[
l_0 = |\mathbf{L}_0|
\]  

(4)

\[
\mathbf{L}_0 \cdot \mathbf{L}_i = |\mathbf{L}_0||\mathbf{L}_i| \cos \alpha_i
\]  

(5)

Projecting the constituent ring vectors in the direction of the closed ring:
\[ |\vec{L}_0| = \sum_{i=1}^{n} (|L_i| \cos \alpha_i) \quad (6) \]

Figure 2 can be used to illustrate the dimensional vector ring model inner product operation, respectively, the angle between the constituent rings and the closed ring, and the projection of each constituent ring in the closed ring vector direction.

Further taking this into the Taylor formula expansion gives:

\[ \Delta_0 = \sum_{i=1}^{n} (\partial h/\partial 1) \Delta l_i = \sum_{i=1}^{n} (\cos \alpha, \Delta l) \quad (7) \]

Suppose that the coordinate point of the dimension vector of each constituent ring in the spatial right-angle coordinate system is \((x_i, y_i, z_i)\), and the coordinates of the closed ring dimension vector are \((x_0, y_0, z_0)\), and the angle between the closed ring and the constituent ring vectors can be obtained from the formula for the vector inner product as:

\[ \cos \alpha_i = (x_0, y_0, z_0) [((x_i^2 + y_i^2 + z_i^2)^{1/2} (x_0^2 + y_0^2 + z_0^2)^{1/2} \quad (8) \]

Where \(x_0 = \sum_{i=1}^{n} x_i, y_0 = \sum_{i=1}^{n} y_i, z_0 = \sum_{i=1}^{n} z_i\), based on the vector addition operation, it can be solved mathematically to solve the 3D vector ring model to obtain the closed ring tolerance.

Further obtained:

\[ \Delta_0 = \sum_{i=1}^{n} \Delta l_i (x_0, y_0, z_0) [((x_i^2 + y_i^2 + z_i^2)^{1/2} (x_0^2 + y_0^2 + z_0^2)^{1/2} \quad (9) \]

3. 3D dimensional tolerance analysis and optimization based on 3DCS

3.1 Dimensional analysis optimization process

The tolerance analysis and optimization of dimensions by 3DCS software is roughly divided into two stages. The first stage is to assemble the assembly according to the actual assembly experience and the pre-given dimensional tolerances when assigning tolerances to the assembly, and to input the tolerance information into the assembly for virtual assembly, so that the sensitivity of different tolerances to the impact of the assembly can be analyzed through the simulation results. The second stage is to adjust the tolerance of the feature tolerance with the largest contribution according to the contribution of each fit to the assembly after the simulation of known tolerances is finished, and perform the simulation again to compare with the previous simulation results until the optimal tolerance is obtained. The flow of 3DCS tolerance analysis is shown in the figure 3. In this way, it is possible to allocate tolerances according to traditional experience and adjust the tolerance allocation according to the contribution of different features to the assembly, taking into account the practicality of tolerances of critical parts with a large impact on the dimensional change of the closed ring, and making the non-critical parts with a small impact on the dimensional change of the closed ring have the largest possible tolerance range, improving the assembly accuracy while reducing the cost [6].
3.2 Example of headlight tolerance analysis of a car

Based on a three-dimensional vector ring model and combined with the Monte Carlo method, a tolerance simulation of a car headlamp is carried out and the results are optimized using the "dichotomy method". Because this paper mainly studies the gap between the turn lamp and the headlight, so the headlight is simplified into bracket, turn lamp and headlight, and other parts have little influence on this gap simulation analysis, so it is ignored. Firstly, use 3DCS to create a new assembly, insert bracket, headlight and turn lamp respectively, after that create feature points and measurement points on turn lamp and headlight and bracket respectively, input GD&Ts. Take the gap between turn lamp and headlight as an example, the allowed design tolerance range of this gap is 3mm, through the simulation analysis report focus on its first 5 influencing factors, other factors that have less influence are not studied here.

According to the traditional equal tolerance allocation method first set the range of tolerance to 1.5 mm, as shown in the figure 4, when using the traditional equal tolerance principle for assembly, the overrun rate is 17.22%, the gap tolerance value to be measured is 6.59 mm, which is far beyond the allowable tolerance range and must be optimized. According to the analysis report it can be seen that the biggest influence on the assembly clearance is the surface profile tolerance of the bracket CadSurf11, which accounts for 22.82%, so the focus is on optimizing the tolerance of this influence factor.

In the actual assembly process, 0mm deviation does not exist, according to the "dichotomy" idea mentioned in the previous article, take the middle value 0.75 between 0mm and 1.5mm to carry out the simulation again, the result is shown in the figure 5, the over deviation rate is after the tolerance adjustment, the tolerance of the assembly gap is 4.82mm, although it still does not reach the design requirement tolerance, but it is closer to 3mm than the previous result, so it proves that the optimization method of tolerance adjustment by "dichotomy" is simple and feasible.
Next, continue to use the "dichotomy method" to take the median value between (0.75mm, 1.5mm) and (0mm, 0.75mm) to obtain 0.375mm and 1.125mm respectively, from the results in figure 6 it is clear that the assembly clearance tolerance is 2.42mm when 0.375 is obtained, and the overrun rate is 0.51%, at this time, the overrun rate as well as the assembly clearance tolerance has been significantly reduced, which has met the initial tolerance design criteria, and when 1.125 is obtained, the assembly clearance tolerance is 3.4mm, which does not meet the design conditions. And so on, we can continue to use the "dichotomy method" in (0mm, 0.375mm) and (0.375mm, 0.75mm) to take the midpoint value, and gradually reduce the tolerance value range, until the optimal point is obtained that satisfies the condition.

![Figure 6. Simulation results for Range=0.375.](image)

The median values taken are brought into 3DCS for simulation. By table 1 we can get that when the tolerance range is 0.5625mm, 0.1875mm and 0.375mm, the overrun rate is very low, and the assembly clearance meets the design requirements. Therefore, when the tolerance range is adjusted to 0.5625mm, it is the best advantage of the lowest economic cost and satisfying the design conditions.

| Tolerance values | 0  | 0.1875 | 0.375 | 0.5625 | 0.75 | 1.125 | 1.5 |
|------------------|----|--------|--------|--------|------|-------|-----|
| Assembly Tolerance(mm) | 0  | 2.28   | 2.42   | 2.56   | 4.82 | 3.4   | 6.59 |
| Excess rate (%)      | 0  | 0.5    | 0.51   | 0.46   | 6.21 | 4.5   | 17.22 |

4. Conclusion

According to the traditional principle of equal tolerance allocation, a "dichotomous method" of tolerance allocation is explored, based on the dimensional vector ring model, Monte Carlo method of 3DCS software is used to adjust and optimize the characteristic tolerances of the influencing factors with the greatest contribution, and finally the optimal tolerance results are obtained. The method is validated by simulation analysis combined with the example of automobile headlight, which further illustrates the superiority and reliability of the improvement scheme. The virtual assembly of the part using 3DCS to adjust the tolerance greatly saves the time of the actual assembly of the part and provides guidance for the design of the initial stage of the part.

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