# Research on Multi-Level Optimization of A/C Bi-Rotary Milling Head Using TRIZ

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***Abstract* —In order to meet the demand of a large torque of A/C bi-rotary milling head, this paper made a research on the multi-level optimization strategy for A/C bi-rotary milling head based on the guidance of TRIZ. Firstly, the technical contradiction of bi-rotary milling head was analyzed, and inventive principles were obtained by TRIZ contradiction matrix, and then were mapped to specific solutions. Secondly, the technical contradiction of bi-rotary milling head was turned into physical contradiction. Through TRIZ separated principle, the invention principles of the physical contradiction were obtained. The invention principles were mapped to specific solutions, too. Thirdly, all invention principles were sorted via recommendation times. Then, through using the method of "Cluster In Cluster Out" (CICO) in TRIZ, the inventive principles, which had been recommended frequently, were analyzed again in this stage. Some appropriate solutions about these inventive principles were found out. Fourthly, the product design level of all solutions was analyzed and the product design optimization level for each solution was determined. Finally, feasibility analysis was performed on the obtained solutions, and optimal strategy was used in A-axis box's structural optimization of bi-rotary milling head which gainedgood result.**

***Keywords- TRIZ; bi-rotary milling head; contradiction; structure; optimization***

## I. INTRODUCTION

Five-axis CNC machine is the important manufacturing equipment in the aerospace, shipbuilding, energy, defense industry and other industries. Bi-rotary milling head is a key component of the five-axis machine tools. Especially the heavy load bi-rotary milling head, with high-power and high-torque, is gaining more and more attention now. Bi-rotary milling head has been researched from the 1980s in USA [1]. This area of technology was researched until after 2000 in China. Bi-rotary milling head can be divided into two styles: torque motor drive type and mechanical drive type [2, 3, 4, 5]. The transmission of torque motor drive milling head is simple, but the torque of motor is usually only a few hundred n • m, cannot meet heavy cutting requirements. The transmission of mechanical drive milling head is complex, which usually used worm gear system or multiple gear system. So, this transmission is large and heavy. For heavy cutting needs, bi-rotary milling head needs high output torque. There are two main methods to increase torque. Firstly, using large-torque drive motor. Secondly, using mechanical drive way. Since there is not large-torque drive motor to meet the heavy cutting requirement at present, it can only use the mechanical drive type. Mechanical drive bi-rotary milling head has big volume and weight, affect the dynamic characteristics and cutting precision of milling head. Resolving the conflicts between torque and weight is one of key problem in design of milling head. If simply reduce the weight of milling head, will reduce the stiffness and cutting precision of milling head. Therefore, resolving the contradiction between stiffness and weight is also one of the key problems in the design of bi-rotary milling head.

Generich Altshuller and his colleagues introduced TRIZ (Theory of Resolution of Invention Problem) in1946. They found 40 principles from the study of reportedly 3 million patents. TRIZ is able to create a set of systematic innovation and improvement methodology, its advantage is good at solving complex systems of various types of conflicts. Much experience in applying TRIZ applications to optimization areas of mechanical produce has been amassed, such as fan hub [6], brake [7], washing machines [8], ceramic machinery [9], friction plates [10], trip latch roller pin sub-assembly of air circuit breakers [11], trimming tool [12], actuation system for manipulator upper arm[13] and so on. But the optimization of bi-rotary milling head by TRIZ was reported rarely. The contradictions between torque, stiffness and weight of bi-rotary milling head would be solved by TRIZ in this paper. In the optimization process of bi-rotary milling head by TRIZ, design requirements and improvement parameters would be full account. The reasonable and practical structure optimization program would be finding through solving the invention principles. The level of all optimization programs would be analysis and evaluation. The multi-level optimization strategy would be gain. An optimization example about bi-rotary milling head was discussed at last.

This paper is structured as follows. Section "Introduction of TRIZ Technology" would introduced some methods and techniques about TRIZ. Section "Process of Optimization Program Obtaining by TRIZ" proposed the flowchart for the optimization strategy of bi-rotary mill head using TRIZ. Section "Analysis of Technical Contradiction" founded the key technical contradictions about bi-rotary milling head.

Then these technical contradictions would be analysis through contradiction matrix of TRIZ. Some invention principles were recommended according contradiction matrix. The specific solutions were been find according the invention principles and engineering knowledge. Section "Analysis of Physical Contradiction" discussed the analysis of physical contradictions by separation principles. Some specific solutions will also be recommended in this step. Section "Analysis of CICO Method" analyzed the invention principles of high recommended times and tried to find specific solutions again. Section "Hierarchy Analyses and Decision of Optimization" discussed the level of optimization solutions in the process of produce design. The feasible of these optimization solutions would also be evaluated. The best optimization strategy would be gained. Section "Example" exhibited the optimization of key part about bi-rotary milling head. Some effective result was gained at last.

## II. TRIZ AND OPTIMIZATION PROCESS USING TRIZ

TRIZ is a systematic problem solving technique. The core problem of the invention is to solve the contradiction of products design in TRIZ theory. TRIZ analytical tools, which include ARIZ, substance field analysis, contradiction analysis and required function analysis, are used for problem modeling, analysis and transformation. Contradiction analysis is a powerful tool of looking problem with the new perspective. Contradiction can be classed into technical contradiction and physical contradiction. The technical contractions might be solved by contradiction matrix. The technical contradictions represent the conflict between two subsystems of a system. Contradiction matrix is composed 39 parameters and 40 invention principles. 39 parameters most frequently involved in design are identified in TRIZ theory. The 39-by-39 contradiction matrix for TRIZ analysis enlists solution principles for each combination of "feature to improve" from 39 rows and "worsening feature" from 39 columns. 40 invention principles are used to guide the TRIZ practitioner in developing useful concepts of solutions for inventive situation. For each combination of the "feature to improve" and the "worsening feature", the TRIZ contradiction matrix suggests several candidate from the 40 generalized solution principles [14]. Physical contradictions might be solved by separation principles. The physical contradictions implied inconsistent requirements to physical condition of the same element of a technical system or operation of a technology process. The design problem is codified in terms of technical contradictions, and principles suggested by the contradiction matrix are used for resolving the tradeoff to develop a primary solution concept. The suggested technical contradictions can be formulated into a contradiction statement. The solving process of TRIZ is shown in Figure 1.

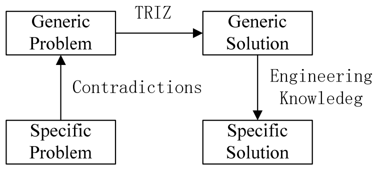


Figure 1. Solving process of TRIZ

The optimization process of bi-rotary milling head is shown in Figure 2.

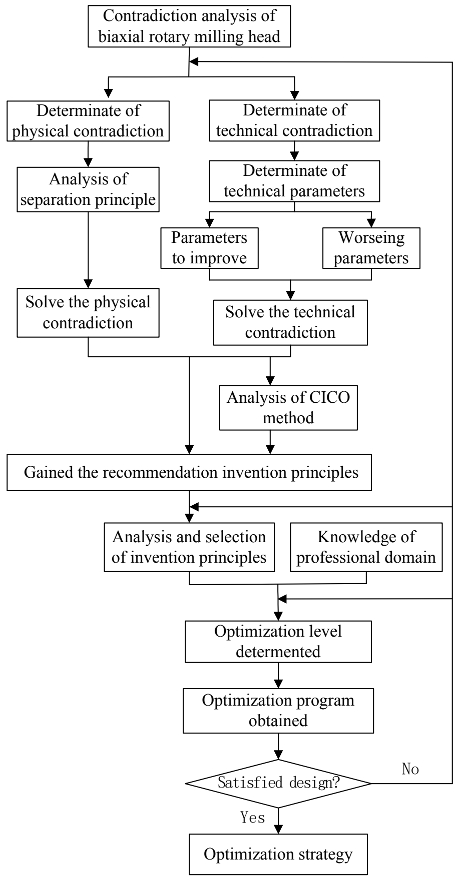


Figure 2. Flowchart for the optimization process of bi-rotary milling head using TRIZ

The question about solving contradiction of bi-rotary milling head is analysis the representative contradictions of system using TRIZ. We would find the general engineering technical program to solve these contradictions. Hence the structure of bi-rotary milling head would be optimization without a significant increase difficulty of system engineering. To solve the contradictions and realize optimization of bi-rotary milling head, we should utilize the professional knowledge and invention principles of TRIZ. On the other hand, we would also evaluate all levels of optimization programs to make sure the actual effect of optimization.

## III. ANALYSIS OF TECHNICAL CONTRADICTION

From the present technologies of A/C bi-rotary milling head, the milling head using torque-motor drive couldn't meet the requirements of large cutting torque. To obtain large cutting torque, the mechanical drive must be used. The milling head of mechanical drives was complex, big and heave. So, the dynamic characteristics of mechanical drive milling head were inferior. The rigidity of gears is low in the mechanical-drive milling head. The accuracy of mechanical drive milling head was lower than the direct drive milling head. The conflict is that the torque and rigidity increase the weight is also increase. Therefore, to improvement the dynamic characters and cute accuracy of bi-rotary milling head, we should reduce the weight of milling head at the mean time keep the large torque-output and rigidity. So the key contradictions of bi-rotary milling head were torque vs. weight and rigidity vs. weight form TRIZ theory. The torque can be replaced with the engineering feature " force" (No. 10). The rigidity may correspond to the engineering feature "intensity "(No.14). The weight can be correlated with the engineering feature "weight of the moving object" (No.1). The candidate solution principles for the combinations of the "feature to improve" force and the "worsening feature" weight of the moving object are listed in Table 1.

TABLE 1 TECHNICAL CONTRADICTION MATRIX OF "FORCE-WEIGHT OF THE MOVING OBJECT"

| Worsening feature / Feature to improve | Weight of the moving object (No.1) |
|---|---|
| Force (No.10) | Invention principles: Counter-weight (IP 8), Segmentation (IP 1), Thermal expansion (IP 37), Mechanical vibration (IP 18) |

The technical contradiction matrix provides "Counter-weight" (IP 8), "Segmentation" (IP 1), "Thermal expansion" (IP 37) and "Mechanical vibration" (IP 18) in Table 1. These invention principles offer statistical guidelines for the current problem. Invention principle 37, "Thermal expansion", can be use in the interference joint way to substitute for other joint ways in the structure design of milling head. Some parts would be cool before assembly. These parts would be expanded at ordinary temperature after assembled. This method could decrease the volume and weight of milling head. The change of gravity, air pressure, altitude and light could cause thermal expansion or contraction. The thermal expansion could also be controlled by controlling the temperature and other factures in the process environment. The thermal expansion could be a precise control in this way.

Invention principle 18, "Mechanical vibration ", can be used in design of milling head at such two ways. One was to add vibration to the milling head itself, to improve the manufacturing efficiency and quality, which has been used in some machine tools at present, such as vibration milling machine, etc. Another was to give a vibration to milling machine to offset its vibration, aimed at reducing the vibration of the milling head, so as to improve the processing accuracy and quality, but the method was rarely reported at present.

For the remaining two recommended invention principles, "Counter-weight" (IP 8) and "Segmentation" (IP 1), it seems that the resolve of this problem was completely with no contribution or no reference value.

Then the engineering parameter "intensity" can be seemed as "feature to improve". The engineering parameter "weight of moving object" can be seemed as "worsening feature". The contradiction matrix provides "segmentation" (IP 1), "counter-weight " (IP 8), "composite materials" (IP 40) and" dynamic" (IP 15) as table 2.

TABLE 2 TECHNICAL CONTRADICTION MATRIX OF "STRENGTH-WEIGHT OF THE MOVING OBJECT"

| Worsening feature / Feature to improve | Weight of the moving object (No. 1) |
|---|---|
| Intensity (No. 14) | Invention principles: Segmentation (IP 1), Counter-weight (IP 8), Composite materials (IP 40), Dynamic (IP 15) |

Analyzing the invention principle 40 "Compound materials". If all characteristics of composite material could meet the requirements of bi-rotary milling head, it was a very good solution to solve such contradiction. But, this kind of compound material is not exist or can't be used in the project at present.

Analyzing the rest three invention principles, it seems that the resolve of this problem was completely with no contribution or no reference value.

## IV. ANALYSIS OF PHYSICAL CONTRADICTION

Assuming that the engineering parameter "the weight of the moving object" is increasing, the structure of bi-rotary milling head can be thicker, so that the shell stiffness of bi-rotary milling head will increase. When bi-rotary milling head bears the cutting load, the deformation will be reduced, the accuracy of bi-rotary milling head will be improved. In other words, the manufacture precision of the bi-rotary milling head is improved. From the above analysis, we can conclude that the weight is bigger, the better manufacture quality of the milling head will be. So we could get an analysis chain 1 shown in Figure 3.

Weight of the moving object——Strength——Manufacture precision

Figure 3 Analysis chain 1

But in another way, if the engineering parameter "Weight of the moving object" gets bigger, the contact force in parts of the milling head will increase and the frictional force between the contact surfaces will rise up. This status would improve the radiation of bi-rotary milling head. The thermal deformation of milling head would be increase. As a result, that will further reduce the manufacturing precision of the bi-rotary milling head. From the above analysis, we can conclude that the less weight is, the better quality of the milling head will be. So we could get an analysis chain 2 shown in Figure 4.

Weight of the moving object——Loss in energy——Manufacturing precision

Figure 4 Analysis chain 2

If we regard the engineering parameter "Weight of the moving object" as a worsening feature (i.e., increase the weight), the energy loss is also a worsening feature. Therefore, these two features have the same change trend. There are not technical contradictions between the two features. In the same way, the manufacturing precision will deteriorate as the above two engineering parameters. In the following step, we can combine analysis chain 1 with analysis chain 2 in order to get a analysis chain with a branch as shown in Figure 5.

Weight of the moving object — Strength / Loss in energy — Manufacturing precision

Figure 5 Analysis chain with embranchment

Next, we make this rule: mark '↑' represents the improvement of engineering parameters and mark '↓'represents the deterioration of engineering parameters . Then, we can see that the analysis chain 1 with trend will be shown as Figure 6.

Weight of the moving object↓——Strength↑——Manufacturing precision↑

Figure 6 Analysis chain 1 with trend

We also can see that the analysis chain 2 with trend shown as Figure 7.

Weight of the moving object ↓ ——Loss in energy ↓ —— Manufacturing precision ↓

Figure 7 Analysis chain 2 with trend

By analyzing the above two chains with change trend, we know that the increase of the engineering parameter "Weight of the moving object " (No. 1) will lead to both the increase and the decrease of "Manufacture precision " (No. 18). So, the parameter of "Weight of the moving object " (No. 1) is expected to be both large and small. From the perspective of TRIZ, it is a self contradiction that one parameter requires both large and small. This self contradiction is also called physical contradiction. For TRIZ, physical contradiction is usually the nature of the problem, which is thought more possible to get a solution. In TRIZ, the solution of physical contradiction is mainly addressed by separation principles. Separation principle can be divided into four categories: separation in space, separation in time, separation in conditions, separation in total and parts. Next, engineering parameter "Weight of the moving object", which is belong to a physical contradiction, was analyzed according to the separation principles.

Firstly, we considered the principle of "separation in space". This method is implement different function/performance in different space division. We must divide the space into several parts reasonably in the first step and it is also a first-seat that we must pay enough attention. After consideration of the separation in space, we can adopt the "Local quality " (IP 3). For this invention principle, we can have the following two mapping method. One is choose different materials in different parties in order to make the whole of the bi-rotary milling head to achieve optimal performance. The other is that finding the best way to hold the forces through the analysis and calculation and maximizing the local properties of the structure, which conforms to the ideas of structural topology optimization method.

Secondly, we considered the "separation in total and parts". This method is needed to distinguish between the local and overall performance of the object and must fully consider the possibility of object localization performance and ensure that the partial performance does not affect the overall function. After thinking of this separation principle, we can use the invention principle "equipotent " (IP 12). In the stress design of mechanical structure, the material which doesn't work on the design of internal structure, namely the low stress or strain energy density of the material is inefficient, can remove. Removing the ineffective or inefficient material step by step, the rest of structure would be optimized. At the same way, for the high stress area, we can optimize them by increasing the material, which conforms to the thoughts of bi-directional evolutionary structural optimization (BESO) of structural topology optimization. According to the structural topology optimization theory, we can make the force trend of the bi-rotary milling head structure consistent. When the total mass remains unchanged, we can make the stress distribution more uniform and reasonable by reducing the maximum stress. On the other hand, when the basic deformation remains the same, the weight of milling head would be reduced by the way of structure optimization.

For the invention principles which were recommended by "separation in time" and "separation in condition", it seems that they have no contribution to the problem or no analogy to the reference value.

## V. ANALYSIS OF CICO METHOD

In the above conflict analysis, we received ten times of invention principles. Five invention principles have the mapping schemes at present. In addition, the rest invention principles also could to find the mapping options. So, all of invention principles were analyzed using CICO approach of TRIZ again. CICO is based on a combination of multiple technologies contradiction of the invention principles for target-oriented classification, whose role is to apply the invention principles after sort by recommended number to find the most likely use of the invention principles. The key of CICO is to generate a list of methods according to the number of the recommended that is the recommended maximum number of inventive principles on the first, while the recommended minimum number of on the last, and then starts from the first invention principles, one by one to analyze [15]. The recommended 10 times invention principles are arranged as shown in Table 3.

TABLE 3 RECOMMENDED TIMES OF INVENTION RINCIPLES

| Sequence number of invention principles | 1 | 8 | 37 | 15 | 18 | 40 | 3 | 12 |
|---|---|---|---|---|---|---|---|---|
| Times of recommended | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |

As can be seen from the table, "Segmentation" (IP 1) and "Counter-weight" (IP 8) appear twice. Due to limit to space, only such two invention principles were analyzed in detail again. "Segmentation" (IP 1) refers to a system due to the weight or bulky and difficult to manipulate, it can be divided into several subsystems, easy to handle. Segmentation principle is similar to product design principles "centralization and decentralization". The function structure would be very complex if functions were too focused. On the other hand, the coupling assembly would be very complex if functions were too fragmentation. Therefore, in the design of bi-rotary milling head, Segmentation principle must be consider carefully to weigh the balance between centralization and decentralization. "Counter-weight" (IP 8) is full use of air, gravity, fluid, etc. lift or compensation the existing system / super system / environment adverse effects. At present, these two principles could not find the mapping scheme in the design of bi-rotary milling head at present.

## VI. HIERARCHY ANALYSES AND DECISION OF OPTIMIZATION

Mechanical product life cycle is comprises product design phase, manufacture phase, sales stage, use and recovery stages. Each stage can be divided into multiple levels. Product design phase include the research and analysis of demand, conceptual design, scheme design, structure design, simulation analysis, structure modifications and drawing output. The optimization scheme of bi-rotary milling head provides optimization guidance for different level of produce design. It is well know that the optimization level is high the optimization effect is well. All of invention principles and corresponding optimization scheme, which obtained by analyzed of technical contradiction, physical contradiction and CICO, would be analyzed to determine the level of produce design. The optimization scheme of "Thermal expansion" (IP 37) is to select a specific connection. This optimization scheme is belong to structure design level in design process of mechanical produce. The optimization scheme of "Mechanical vibration" (IP 18) is to add or eliminate vibration device in bi-rotary milling head. This optimization scheme is belong to structure design level in design process of mechanical produce. The optimization scheme of "Composite materials" (IP 40) is select material before structure design. This optimization scheme is belong to scheme design level in design process of mechanical produce. The optimization scheme of "Local quality" (IP 3) can map to two program. The first one is select material before structure design. It is belong to scheme design level in design process of mechanical produce. The second one is find the best bear-force structure. It is belong to structure design level in design process of mechanical produce. The optimization scheme of "Equal potential" (IP 12) is simulate the distribution and deformation of bi-rotary milling head when the structures bearing the force by Finite Element Analysis (FEA). Some material would be reduced when the deformation of design area is small. On the other hand, some material would be added when the deformation of design area is large. The stress in various parts of milling head would be close to accord. At the same time, the weight of bi-rotary milling head would be reduced. This optimization scheme is belong to simulation analysis level in design process of mechanical produce. The optimization scheme of "Segmentation" (IP 1) is to decompose the structure of milling head. It is belong to scheme design level in design process of mechanical produce. The optimization scheme of "Counter-weight" (IP 8) is to compensate the gravity of milling head. It is belong to concept design level in design process of mechanical produce. All invention principles, which obtained from various conflicts analysis in TRIZ, were corresponded to different levels of produce design. Therefore, multiple levels of optimization strategies could be used in the process of produce design with TRIZ.

The optimization scheme which obtained by TRIZ needs be evaluated from two aspects. The first one is evaluated the executable of optimization scheme. The second one is determined which scheme is the best. Firstly, the feasibility analysis of all optimization schemes is show in Table 4.

TABLE 4 FEASIBILITY ANALYSIS OF OPTIMIZATION SCHEME

| No | Inventive principles | Optimization | Feasibility analysis |
|---|---|---|---|
| 1 | Thermal expansion (IP 37) | Interference Fit to replace other connection mode | According specific head structure to design in assembly, implementation easier |
| 2 | Mechanical vibration (IP 18) | A: vibration cutting<br>B: Initiative to eliminate vibration of milling head | A: Currently existing applications using the method of vibration cutting, but it is difficult to apply to bi-rotary milling head<br>B: the application of eliminate vibrations in bi-rotary milling head have not been reported, it is difficult to achieve |
| 3 | Composites material (IP 40) | Light weight, stiffness composite materials replace conventional metal material | Prospects very good, but now difficult to achieve |
| 4 | Local quality (IP 3) | Different part selected different materials, or find the best force-bear structure | According specific head structure to design, this way can achieve easy by FEA |
| 5 | Equal potential (IP 12) | Stress in milling head is closed to accord | According specific head structure to design, this way can achieve easy by FEA |
| 6 | Segmentation (IP 1) | Structural division of bi-rotary milling head | Apply in the conceptual design stage of bi-rotary milling head, guidance rotary milling head structural decomposition, difficult to achieve, but it can carry out FEA |
| 7 | Counter-weight (IP 8) | Milling Head execute the cutting work in a liquid environment | difficult to achieve |

After the feasible optimization programs were gained, the optimal solution would be determined. Determining the optimal solution is combined with the existing engineering and technical knowledge, to find the most feasible and easy-to-optimization schemes. Analyzing above candidate optimization program, the feasible implementations of part design are program 4 and 5. Above three programs are no conflicts because there are from different areas to optimize the structure of bi-rotary milling head. According to the different stages of product design, select a different optimization methods, or use a variety of optimization methods together to complete the product design optimization, this method known as multi-level optimization strategy.

## VII. EXAMPLE

In the structure design phase of bi-rotary milling head, according to the preliminary design of milling head structure, using method 4 to find the pipes' placement in A-axis box and using method 5 to optimize the structure of A-axis box. Main cutting force of the milling can be calculated by empirical formula. If end mill's material is high speed steel, the work piece's material is steel or malleable iron, the main milling force empirical formula is as follow [16].

$$F_c = C_F \cdot k_F \cdot a_e^{0.86} \cdot a_f^{0.72} \cdot d_0^{-0.86} \cdot z \cdot a_p \quad (1)$$

Wherein, $C_F$ - cutting coefficient; $k_F$ - correction coefficient; $a_e$ - cutting width (mm); $a_f$ - the amount of feed per tooth (mm); $d_0$ - cutter diameter (mm); $z$ - Teeth cutter; $a_p$- back engagement (mm).

Look-up table or other amount determined in accordance with the value of the actual situation: $C_F = 669$, $k_F = 0.92$, $a_e = 8mm$, $a_f = 0.1mm$, $z = 6$, $d_0 = 50mm$, $a_p = 15mm$.

The above parameters into the calculation formula can be obtained:

$$F_c = 669 \times 0.92 \times 8^{0.86} \times 0.1^{0.72} \times 50^{-0.86} \times 6 \times 15 = 2182.73N$$

According to the ratio relationship of each milling cutter component, the vertical component $F_v$,the horizontal component $F_e$ and longitudinal component $F_f$ , can be calculated respectively as follow.

$$F_v = 0.38 \times 2202.82 = 829.44N$$

$$F_e = 1.1 \times 2202.82 = 2401.00N$$

$$F_f = 0.25 \times 2202.82 = 545.68N$$

Force $F_v$ was along the axial of milling cutter. Force $F_e$ and $F_f$ were lateral loading of milling cutter. According to the connection status of each part of the A-axis milling head body, stress condition of A-axis milling head body is show in Figure 8.

The stress functions were as follow.

$$\begin{cases} -F_1 + F_4 = -F_e & (2) \\ -F_2 + F_5 = -F_f & (3) \\ -F_3 = -F_v & (4) \\ -0.176F_1 - 0.105F_4 = -0.348F_e & (5) \\ -0.176F_2 - 0.105F_5 = -0.348F_f & (6) \end{cases}$$

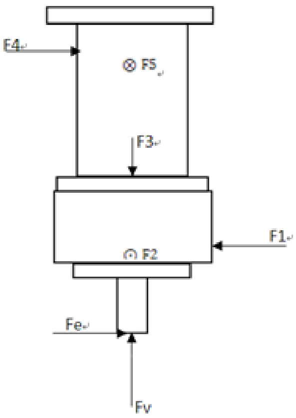


Figure 8 Stress condition of A-axis milling head body

The solution was as follow.

$$\begin{cases} F_1 = 3870.65N \\ F_2 = 879.69N \\ F_3 = 829.44N \\ F_4 = 1469.65N \\ F_5 = 334.01N \end{cases}$$

A-axis box is a key part of bi-rotary milling head. It needs to design a number of pipes in A-axis box. So the method of structural topology optimization can be used in determining the placement of the pipes. The force in A-axis box is shown in Figure 9.

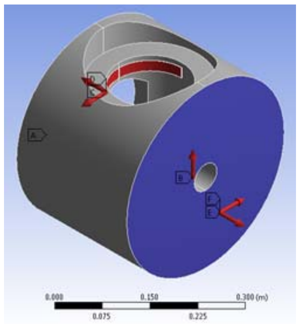

Figure 9 Force in A-axis box

The material of A-axis box is structural steel, which having the density of 7850Kg / m$^3$, the elastic modulus of 2*10$^{11}$Pa, the Poisson's ratio of 0.3. The mesh uses Tetrahedrons method. The output results were "Total Deformation", "Equivalent Elastic Strain" and "Equivalent Stress", corresponding to the total deformation, equivalent elastic strain and effective stress respectively.

Using method 4, the results of topology optimization are shown in Figure 10. The red part of A-axis box is recommended to remove. According to the proposal, several design and calculations were done. The optimization of material removal is shown in Figure 10. Some pipes were design in A-axis box and these pipes can be use as gas channels, liquid channels, electricity channels and other channels.

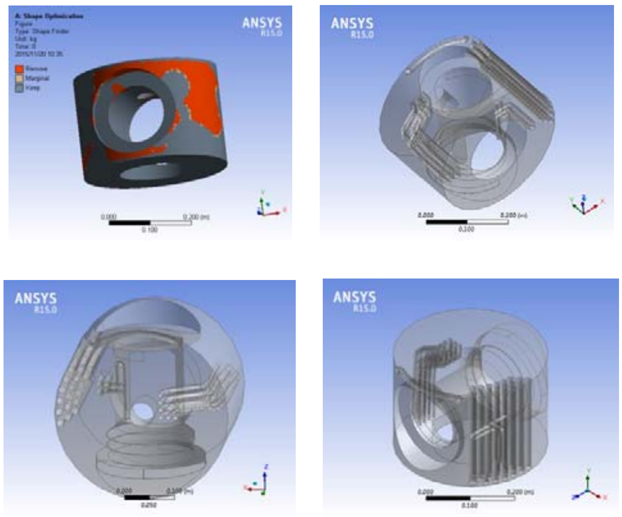


Figure 10 Results of topology optimization

Using method 5, the total distortion, equivalent elastic strain and effective stress of A-axis box before optimization is shown in Figure 11.

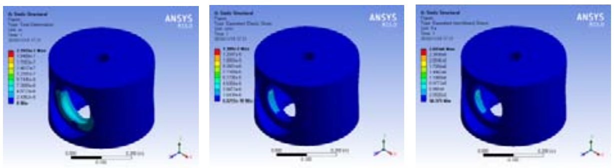

Figure 11 Total distortion, equivalent elastic strain and effective stress of A-axis box before optimization

Using method 5, the total distortion, equivalent elastic strain and effective stress of A-axis box after optimization is shown in Figure 12.

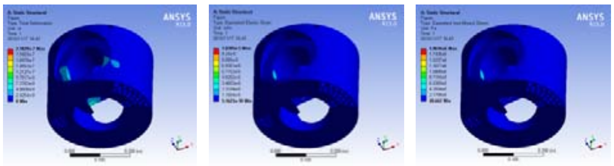

Figure 12 Total distortion, equivalent elastic strain and effective stress of A-axis box after optimization

The contrast of optimization results is shown in Table 5.

TABLE 5 CONTRAST OF OPTIMIZATION RESULTS

| Result / Operation | Quality (Kg) | Total Deformation (m) | Equivalent Elastic Strain (m/m) | Equivalent Stress (Pa) |
|---|---|---|---|---|
| Optimization Before | 113.94 | 2.1925* 10^-7 | 1.389* 10^-5 | 2.693* 10^6 |
| Optimized | 104.25 | 2.1829* 10^-7 | 1.0395* 10^-5 | 1.9616* 10^6 |
| Reduce Amount | 8.50% | 0.44% | 25.16% | 27.16% |

From the table, the quality of A-axis box were reduced, the total deformation, equivalent elastic strain and effective stress were also reduced. The result is shown the good effect of optimization.

## VIII. CONCLUSIONS

In order to improve the indicators of torque and stiffness in bi-rotary milling head, a multi-level optimization scheme is obtained by in-depth analysis using TRIZ. The technical contradictions, physical contradictions and CICO method were researched detailed in design of bi-rotary milling head. All of invention principles were analyzed in detail. The specific solutions were found. The feasibility of optimization strategy was evaluated and the final optimization scheme of bi-rotary milling head was determined. Finally, according above optimization scheme, the topology optimization was used in A-axis box and got the effective result in this paper. Future research will adapt this optimization strategy to the specific case design of bi-rotary milling head. The evaluation and feedback of optimization effect in bi-rotary milling head will also be research for the future.

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