Lightweight optimization design of arm frame for aerial work platform based on NSGA-II algorithm

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Abstract: In the previous lightweight design of the arm of aerial work platform, it is difficult to balance the relationship between lightweight and stiffness reduction. This paper proposes a lightweight design that minimizes the variation stiffness while reducing weight. Taking the arm mass and stiffness variation as the objective, which constrained by yield strength and stiffness of the material, the Pareto front of each arm section size is obtained by the second generation of elite strategy non-dominated sequencing genetic algorithm (NSGA-II). Finally, the finite element model is established by ANSYS to compare the static and dynamic performance of the arm before and after optimization. The results show that the weight of the optimized arm is reduced by the original 13.3%, lightweight effect is remarkable.

1. Introduction
As the main component of the aerial work platform, the arm structure occupies 58%-67% of the whole vehicle. Therefore, the lightweight optimization design for the arm is an effective way to reduce the overall mass. In recent years, topology optimization has been applied in the optimization of crane arm sections. Wang Xin et al used the Optistruct module of the commercial software HyperWorks to optimize the topology of the crane arm section to obtain the optimal section topology. Zhang Xianhuan et al applied the forward design method to reduce the weight reduction effect of the tower crane arm. Li Qianjin et al use ANSYS to optimize the weight of the aerial work platform arm with the mass as objective, and succeeded in reducing the mass by 6.3%. In order to minimize the variation in stiffness of the arm while reducing weight, the NSGA-II is used to find the better size of the arm section. Taking the arm mass and stiffness variation as the objective, which constrained by strength and stiffness. The results show that the weight of the optimized arm structure is reduced by 871kg, accounting for 13.3% of the original mass. Finally, the statics and dynamics performance of the before and after optimized arm structure are compared under the typical working conditions. The results
show that the lightweight effect is obvious, and the method can provide a reference for the lightweight design of the arm of aerial platform.

2. The finite element model and optimization model

In this paper, optimization model has five arms, which total weight is 6518kg, and section is rectangular. Using APDL language in ANSYS to establish parametric finite element model of each arm. The finite element model of the arm of aerial platform is shown in Figure 1.

![Finite element model of arm frame for aerial work platform](image)

**Fig. 1** Finite element model of arm frame for aerial work platform

**Fig. 2** section of the arm

2.1 working condition

Six typical working conditions are selected for calculation, in which the dangerous working condition-4 is taken as the optimal calculation condition. Finally, the before and after optimized structure are compared under the last conditions. The typical working conditions are described in Table 1.

| Working condition | 1  | 2  | 3  | 4  | 5  | 6  |
|-------------------|----|----|----|----|----|----|
| Amplitude angle (°) | 0  | 28 | 50 | 70 | 76 | 80 |
| elongation (mm)    | 1739 | 2355 | 4082 | 8140 | 8750 | 8750 |
| Arm head force (N) | 265416 | 209385 | 199663 | 224958 | 244859 | 263870 |
| Level hole force (N) | 261444 | 211738 | 209863 | 237061 | 258001 | 277594 |

2.2 Optimization of arm section size

The arm section is rectangular, so the optimized sizes of the arm are flange plate and web, as shown in Figure 2. The size to be optimized in the figure is the section height $H_i$, section width $W_i$, section web thickness $C_i$, thickness of flange plate on the section $S_i$, and thickness of flange plate under the section $X_i$, $i=1,2,3,4,5$.

2.3 Optimization mathematical model

In the lightweight optimization design, the maximum stress of the optimized arm under all working conditions is required to be no more than the ratio of its yield strength and safety factor. Since the load of working condition has been enlarged to the safety factor in this paper, the stress constraint is no more than the yield strength of the material. In addition, the maximum displacement of the optimized arm head in the amplitude plane cannot exceed the allowable value. Finally, under the condition of satisfying the constraints of stress and displacement, the
optimization objective is to minimize the arm mass and stiffness variation. The mathematical model is as follows:

$$\begin{align*}
\text{min} & \quad M, \Delta K \\
\text{s.t.} & \quad \sigma_{\text{max}} \leq \sigma \\
& \quad U_{\text{max}} \leq U \quad \forall i \in [i-20, i+20], i=1,2,3,4,5 \\
& \quad \forall j \in [j-10, j+10], j=1,2,3,4,5
\end{align*}$$

(1)

Where: $M, \Delta K$ are the arm mass and stiffness variation; $\sigma_{\text{max}}$ is the maximum stress of the arm; $\sigma$ is the yield strength of the material; $U_{\text{max}}$ is the maximum displacement of the arm in the amplitude plane; $U$ is the allowable displacement value; $i$ is the arm section height and width dimension value; $j$ is the arm section web and Flange plate thickness dimension value. Where $\Delta K$ can be transformed into the minimum displacement variation after optimization of the arm end, as shown in equation (2)

$$\Delta K = f - f_0$$

(2)

Where, $f_0$ and $f$ are the displacement before and after optimization of the arm head, which $f$ can be divided into the static displacements $f_z$ and $f_y$ of the arm head in the amplitude plane and the rotation plane, as shown in formula (3). $f_z$ and $f_y$ are calculated by the amplification coefficient method, and the calculation formulas are (4), (5):

$$f = \left( f_z^2 + f_y^2 \right)^{1/2}$$

(3)

$$f_z = \frac{1}{1-0.9 N_{\text{cry}}} \left( f_{\text{wz}} + \Delta z \sum_{i=1}^{k-1} \frac{H_{i+1}}{l_{i+1}} \right)$$

(4)

$$f_y = \frac{1}{1-0.9 N_{\text{crz}}} \left( f_{\text{wy}} + \Delta y \sum_{i=1}^{k-1} \frac{H_{i+1}}{l_{i+1}} \right)$$

(5)

Where: $N$ is the axial pressure on the arm head; $f_{\text{wz}}$ and $f_{\text{wy}}$ are the arm head deflections caused only by the transverse load of the amplitude and the rotation plane when the axial pressure equal zero; $N_{\text{cry}}$ and $N_{\text{crz}}$ are the critical forces of the arm head on the amplitude plane and the rotation plane; $\Delta$ and $\Delta$ are the lateral gap between two adjacent arms, taking $1 \sim 3\text{mm}$; $H_{i+1}$ is the distance from the arm end to the head; $l_{i+1}$ is the distance from the end of the $i+1$ arm to the head of the $i$ arm; $k$ is the number of telescopic arms. Then the optimization objective $\Delta K$ is transformed into $f_z$ and $f_y$.

3. Multi-objective optimization

3.1 Optimization method

The second generation of non-dominated sorting genetic algorithm with elite strategy (NSGA-II)[5] is an improved algorithm of the traditional genetic algorithm. It continues the "survival of the fittest" criterion of the genetic algorithm, and then reduces the complexity of the non-dominated sorting genetic algorithm, with the advantages of fast running speed and good solution convergence. NSGA-II has the ability to find multiple Pareto optimal solutions in the optimization process, and can handle various types of objective numbers and constraints without imposing some mathematical relationships. So it can solve the problem of minimum mass and stiffness variation. The optimization flow of this paper is shown in Figure 3.
2.2 Design variable and Result process

For the design size of the initial input, firstly, the genetic algorithm transforms each variable into the form of binary coding, and then randomly generates the initial population. Then, the population is selected and evolved through crossover and mutation operations. The crossover algorithm uses the simulated binary crossover[6], and the following descendants are generated by the parents $x_a$ and $x_b$, as equations (6) - (9) show. The variation uses the polynomial variation method. For details, see the literature[7]. In this paper, the probability of cross variation is 0.9, and considering the elite strategy, the offspring and the parent are combined to make the new species group more tend to be elite.

$$y_1(k) \leftarrow \frac{1}{2} \left[ (1 - \beta_k) x_a(k) + (1 + \beta_k) x_b(k) \right] \quad (6)$$
$$y_2(k) \leftarrow \frac{1}{2} \left[ (1 + \beta_k) x_a(k) + (1 - \beta_k) x_b(k) \right] \quad (7)$$

Where $\beta_k$ is a random number generated by the probability density of formula (6):

$$PDF(\beta) = \begin{cases} \frac{1}{2} (\mu + 1) \beta^\mu, & 0 \leq \beta \leq 1 \\ \frac{1}{2} (\mu + 1) \beta^{\mu+1}, & \beta > 1 \end{cases} \quad (8)$$

Where, $\mu$ is any non-negative real number, $\mu \in [0,5]$, $\beta$ can be obtained by (7)

$$r \leftarrow U[0,1], \beta \leftarrow \begin{cases} (2r)^{-0.5}, & r \leq 0.5 \\ (2 - 2r)^{-0.5}, & r > 0.5 \end{cases} \quad (9)$$

For the multi-objective optimization problem, there are $n$ objective components $f_i(x)$, $i=1,2,\ldots,n$, and any two decision variables $x_a$ and $x_b$ are given. If following two conditions are true, $x_a$ is said to dominate $x_b$: (1) For $\forall i \in 1,2,\ldots,n$, always have $f_i(x_a) \leq f_i(x_b)$; (2) $\exists i \in 1,2,\ldots,n$, makes $f_i(x_a) < f_i(x_b)$. For a decision variable, if there are no other decision variables that can dominate him, then the decision variable is called a non-dominated solution. In this paper, the non-dominated solution set $X_i$, $i=1, 2,\ldots, 25$ of the section sizes of the arm is obtained by non-dominated sorting, furthermore, which is brought into ANSYS for modeling calculation, and the stress and displacement constraints will be adopted at the same time. Finally, the optimized structure is compared with the static and dynamic performance of the structure before optimization.
3 Analysis of Result

3.1 Lightweight results

Through many experiments, it is found that when the number of popular are 50 and the number of evolutionary iterations is 500, there is a better convergence effect. The optimization iterative process is shown in Figure 4. The 500th generation population is selected as the final optimized population, and the optimal solution is selected in this group. The change curve of arm displacement with mass is shown in Figure 5. Point A is the optimal solution point. The Pareto frontier obtained by optimization is shown in Figure 6.

![Optimized iterative process](image1)

![The curve of displacement with mass](image2)

![Pareto frontier](image3)

The optimized size has been rounded, and the maximum stress and displacement of each arm under the dangerous condition meet the requirements. The optimized result show that the weight after optimization is 5657kg , which is reduced 13.3% of the original mass, that is 6518kg.

3.2 Comparison of static performance

The strength and stiffness of the arm before and after optimization were analyzed and compared under six working conditions. The comparison results are shown in Table 2. The displacement and stress distribution under dangerous conditions are shown in Figure 7,8. According to the comparison data, it can be seen that, under all working conditions ,the maximum stress of the optimized arm is reduced, and the maximum displacement is increased, but it is still within the allowable range, so the static performance of the optimized structure is stable.

| Working condition | Maximum stress /Mpa | Maximum displacement/mm |
|-------------------|----------------------|-------------------------|
|                   | Initial  | Optimized  | Variation | Initial  | Optimized  | Variation |
| 1                 | 612.45  | 537.36     | 75.09     | 282.95   | 285.26     | 2.31      |
| 2                 | 492.02  | 490.18     | 1.84      | 375.25   | 382.07     | 6.81      |
3.2 Dynamic performance comparison

The modal analysis is carried out before and after optimization of the arm under dangerous conditions, and the first five modal frequencies and vibration modes of the arm are obtained. The modal comparison is shown in Table 3, and the main modal comparison is shown in Figure 9. Comparing the data, it can be seen that the vibration frequency difference before and after the first five-step optimization is small, and the vibration mode changes are not large. The dynamic performance of the optimized structure meets the requirements.

**Tabla 3** Primera 5 ordenes Modals Frecuencias del brazo Optimado (Hz)

| Order | Initial     | Optimized   | Variation | Mode description                   |
|-------|-------------|-------------|-----------|------------------------------------|
| 1     | 0.15156     | 0.16646     | 0.0149    | arm Z direction first-order bending |
| 2     | 0.43379     | 0.45008     | 0.0163    | arm Y direction first-order bending |
| 3     | 0.94420     | 0.91540     | 0.0288    | arm Z direction second-order bending |
| 4     | 1.6012      | 1.5787      | 0.0225    | arm Y direction second-order bending |
| 5     | 2.2967      | 2.2494      | 0.0473    | arm Y direction third-order bending |

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**Fig 7** Comparación de resultados de desplazamiento  

**Fig 8** Comparación de resultados de esfuerzo
Fig 9 Comparisons of five Modal Vibration Modes Between Initial and Optimal Arm

4. Conclusion
In this paper, the second generation of non-dominated genetic algorithm (NSGA-II) is used to optimize the arm of aerial platform, which minimizes variation stiffness while reducing weight. Meanwhile, the statics and dynamics performance of the arm after optimized are similar to that before optimization. The arm weight is reduced by 871kg, accounting for 13.3% of the original mass, which effect is obvious. The results can provide design suggestions for designers.

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