Multi-objective Optimization of the Rapidly Assembled Helipad Deck

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Abstract. Aiming at the potential edge bearing problem of the helipad deck, as well as the contradiction between the deck weight and the bearing capacity, a multi-objective optimization design method is proposed in this paper. On the condition of avoiding the most dangerous taking off and landing situations, carrying out the layout of the plane size ranges and the static analysis of the current size by establishing plane coordinate system and deck size constraint inequality. The deck design variables are confirmed based on the deck weight, processing capacity and other constrains, so as to establish the quadratic polynomial response surface model(RSM) of the objective function, and experimental design sample points which uniformly distributed in the design space are obtained through Latin square hypercube sampling(LHS) method. The multi-objective optimization of the deck is performed using the Screening method to obtain the pareto feasible solutions and the response relationship between the design variables and the objective function, which provides the basis for the design of deck size and connector.

1. Introduction
With the rapid development of aviation industry in our country, helicopters are increasingly used in daily life. Especially in all kinds of emergencies and natural disasters, helicopters are widely used in passenger and cargo transportation, emergency rescue, logistics and so on. It plays an increasingly important role in all these areas. However, limited by complex terrain and other environments, helicopters are often unable to land directly which causes serious loss of life and property because of lack of enough time for rescue. To solve this problem, a kind of helipad can be carried easily and paved rapidly is needed.

The rapidly assembled helipad can be divided into two categories according to whether it has landing legs: 1) One of them is rapidly assembled helipad with legs which is mainly applied to forest cutting, mineral exploration and other fields. It is suitable to be used in mountainous areas, steep slopes and other rough terrain; 2) The other is deck type rapidly assembled helipad[1-3] which is mainly applied to medical rescue, military and other fields. It is suitable to be used in grassland, farmland, desert and gravel environment.

In the aviation emergency rescue area, different types of helicopters are used according to different rescue missions, the number of airborne, land topography and some other conditions. Medium and small-scale skid helicopter is also applied to family rescue and most health assistance. It requires smaller landing area and low requirement for rapidly assembled helipad. Wheeled helicopter is mainly
applied to major industrial accidents and natural disasters which has great carrying capacity and bigger take-off weight. It requires bigger landing area and high requirement for rapidly assembled helipad.

This paper focuses on helicopter emergency rescue. A size optimization design method of deck type rapidly assembled helipad is put forward in this paper by taking a kind of three-point helicopter for example. The main material of the deck is high density polyethylene. The deck unit can be connected by stainless steel connectors. When we plan the size of the deck unit, we should firstly confirm the size range according to actual rescue conditions, transportation conditions, etc. And then we should conduct dimensional optimization analysis according to the type of support aircraft to confirm the size of the deck unit.

2. Size range of the deck

2.1. Size planning
We should consider the transportation, assembly, loading and disassembly, etc when we plan the size of the deck. The main modes of transportation of the helipad mainly include hoisting and airborne, so the size of the deck unit should meet the size requirement of hoisting and the size of the cabin door. The size of the deck unit should not be too large, otherwise it is inconvenient to carry and install.

The most important thing is to minimize the marginal load after assembling the decks. The relief ground is usually soft grass, fields, sand and so on while high density polyethylene is a kind of elastic material. It is inevitable to have large deformation caused by marginal load[4]. So, we should plan the size of the deck for the helicopter wheel's imprint size to reduce the possibility of marginal load.

2.2. Size range planning
The situation that the wheels land on the deck junction is the first thing to consider and unavoidable. We should try to avoid multiple wheels landing on the deck junction at the same time in the design. We suppose a wheel has landed on the deck junction. Then we should try to avoid the second wheel landing on the deck junction in this case. Only three situations should be analysed because of the symmetrical structure of wheels. The layout of the wheel areas is shown in figure 1. Twelve typical points are chosen: A1 (x_{a1}, y_{a1}), A2 (x_{a2}, y_{a2}), B1 (x_{b1}, y_{b1}), B2 (x_{b2}, y_{b2}), C1 (x_{c1}, y_{c1}), C2 (x_{c2}, y_{c2}), D1(x_{d1}, y_{d1}), D2 (x_{d2}, y_{d2}), E1 (x_{e1}, y_{e1}), E2 (x_{e2}, y_{e2}), F1 (x_{f1}, y_{f1}), F2 (x_{f2}, y_{f2}).

Let the transverse dimension of the deck unit be \( l_x \) and the longitudinal dimension be \( l_y \). The junction point of the deck is \( L (x_L, y_L) \).

As shown in figure 2, coordinate system \( O_{xy} \) can be set up when the wheel a lies on the junction point of the deck.
The following conditions need to be met if other wheels do not lie on the edge of the deck unit:

\[(n_i l_x + x_i - x_1)(n_j l_y + y_j - y_1) > 0\]

\[(n_i l_y + y_i - y_1)(n_j l_x + x_j - x_1) > 0\]

where \(i = b, c, d, e, f, j = c, d\).

Coordinate system can be set up at the geometric center of the wheel b when the wheel b lies on the junction point of the deck. In this case, \(i = a, c, d, e, f, j = c, d\).

Coordinate system can be set up at the geometric center of the wheel c when the wheel c lies on the junction point of the deck. In this case, \(i = a, b, d, e, f, j = a, b, e, f\).

2.3. Planar size range planning

In practice, planar size of the deck was restrained by the time of splicing and transportation. So in the following calculation, we set \(n_x \leq 4\), \(n_y \leq 4\), \(1000\text{mm} \leq l_x \leq 2400\text{mm}\), \(1000\text{mm} \leq l_y \leq 2400\text{mm}\). The transverse size range and the longitudinal size range of the deck can be shown in figure 3 and figure 4 by solving the restraint conditions in the previous section.
As shown in figure 3 and figure 4, the transverse size of the deck unit is sensitive to the distance between wheels, and it's value range is small and discrete. It is because the number of wheels is so large that there are too many restraint conditions on size. The transverse size can be determined to 1500 mm by confirm the size range: 1496.7<lx<1503.3. The restraint conditions on longitudinal size are much less so the size range is wider. The process of optimization is shown in figure 5.

![Figure 4. Range of longitudinal size.](image)

3. Static analysis of the deck

3.1. Buildup of model

Size range of the deck thickness can be confirmed according to the planar size range in section 2.3, requirement of deck unit's dead-weight and processing craft. On this basis, the three-dimensional model of the deck can be built as shown in figure 6. lx stands for the transverse size, ly stands for the longitudinal size, h represents for the thickness of the deck, d represents for the the diameter of the linking hole. As shown in figure 7, the finite element mesh can be refined partly according to the bearing condition and the contact surface.
3.2. Static analysis

High density polyethylene is chosen in this paper of which the density is 952Kg/m$^2$ and the elasticity modulus is $1.07 \times 10^9$ N/m$^2$. The relational expression is shown as follows according to the constitutive model[5-6] researched by Kown, etc.

$$Y(\varepsilon) = \begin{cases} E\varepsilon & (\varepsilon \leq \varepsilon_y) \\ d \left[ a(\varepsilon + b)^{\varepsilon - 1} - a(\varepsilon + b)^{\varepsilon - \varepsilon_y} \right] + e & (\varepsilon_y \leq \varepsilon \leq \varepsilon_e) \\ a\varepsilon\varepsilon^N & (\varepsilon_e \leq \varepsilon \leq \varepsilon_y) \\ k\exp(M\varepsilon^n) & (\varepsilon \geq \varepsilon_y) \end{cases}$$

(2)

The stress-strain curve fitted in MATLAB is shown in figure 8. As we can see from the picture, the relation between stress and strain is linear when strain is less than $\varepsilon_y$.

High density polyethylene is a kind of high-molecular polymer. Some filler and auxiliaries would be added in the deck during the course of fabrication. And it’s mechanical property could be affected by temperature and density greatly. So, we calculate the allowable stress of the material according to 1.5 times the safety factor.

The helicopter has a certain speed while landing vertically which causes a dynamic load on the deck[7-8]. Therefore, load factor should be taken into consideration when conduct static analysis. The vertical force $F_z$ between the wheel and the landing surface is:

$$F_z = (1+C_v\delta)C_o\delta^n$$

(3)

In the formula, $C_v$ stands for tire force coefficient, $\delta$ stands for the compression of the tire, $n$ stands for the tire force index. The relation between the magnitude of $F_z$ and the draft gear travel could be
described by an appropriate clothoid of which the magnitude of the peak is related to weight, buffer performance and landing speed. When the helicopter drops at a large speed for hard landing, we set the load factor to 3.5 and consider the safety factor for load of 1.5. The deck is loaded with a constant while the linking hole is subjected to horizontal force. The static analysis result of the deck is shown in Table 1.

Table 1. Static analysis result of the deck.

| Mass of the deck unit |
|-----------------------|
| M (kg)                |
| 13.748                |

| Maximum equivalent stress |
|---------------------------|
| Σ (MPa)                  |
| 13.748                   |

| Maximum equivalent strain |
|---------------------------|
| Ε (mm/mm)                |
| 0.129                    |

4. Buildup of response surface model

4.1. Confirming the design variables
For the rapidly assembled parking apron, the larger the deck unit is, the shorter the assembly time will be, the main influence factors are the transverse length \( l_x \) and the longitudinal length \( l_y \). The larger the deck thickness is, the stronger the bearing capacity will be. But the deck would be too heavy to carry if the transverse length \( l_x \), the longitudinal length \( l_y \) and the deck thickness are too large. Though the diameter of the linking hole \( D \) has little effect on weight and maximum equivalent stress, a nonnegligible transverse force would generate which would operate on the linking hole and the connector. In this respect, the diameter of the linking hole and the edge distance become important factors of transverse force. \( l_x, h, D \) are chosen as the design variables while the transverse length has been determined in section 2.3 and the value range is shown in Table 2.

Table 2. Value range of the design variables.

| Design variables | Value range (mm) |
|------------------|------------------|
| \( l_y \)        | (1200, 1500)     |
| \( h             \) | (20, 30)         |
| \( D             \) | (28, 38)         |

4.2. Latin Hypercube Sampling
The choice of test points is very important when constructing the response surface while choosing the test points randomly could influence the construction of response surface. There are three design variables in the optimization of the deck and take samples by LHS. LHS is helpful to select sample points of experiment design more evenly by optimizing the distribution of the input values. 15 sample points are selected and the design space with two factors is shown in figure 9 in which the sample points are equally distributed.

Figure 9. Distribution of test points.

4.3. Quadratic polynomial response surface
Considering that the design variables and the variable to be optimized are not completely linear, the quadratic polynomial response surface model is adopted to predict non-experimental points response. The mathematical model expression is:

\[ \hat{y}(x) = a_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} c_{ii} x_i^2 + \sum_{1 \leq i < j \leq n} d_{ij} x_i x_j \]  

(4)

In the formula, \( \hat{y} \) stands for the response surface prediction, \( a_0, b_i, c_{ii}, d_{ij} \) stand for the constant term and the undetermined coefficients of the primary, secondary and cross terms respectively, \( x_i \) and \( x_j \) are design variables and \( n \) is the number of design variables. Experimental design points should be subjected to polynomial regression analysis to verify the fitting accuracy of the response surface model.

The undetermined coefficient vector \( A(a_0, a_1, ..., a_s) \) could be acquired by least squares method [9-10]. And that:

\[ A = (D^T D)^{-1} D^T Y \]  

(5)

\[ s = (n+1)(n+2)/2 \]  

(6)

\[ D = \begin{bmatrix} D_{11} & \cdots & D_{1s} \\ \vdots & \ddots & \vdots \\ D_{s1} & \cdots & D_{ss} \end{bmatrix} \]  

(7)

In the formula, \( s \) stands for the number of the undetermined coefficients, \( D \) stands for the basis function matrix, \( Y \) is the response vector at \( L \)-th test point which could obtained through AWB DX, \( D_{ij} \) is the value of the design variables' derivation function corresponding to the \( i \)-th regression coefficient at the \( j \)-th test point.

The quadratic non-linear polynomial is converted to the linear regression to verify the fitting situation of the sample points and use the multi-correlation index [10] \( R^2 \) to evaluate the fitting situation:

\[ R^2 = 1 - \frac{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2} \]  

(8)

In the formula, \( N \) is the number of the test points, \( y_i \) is the actual response value, \( \bar{y} \) is the average value of the actual response values. The closer \( R^2 \) is to 1, the higher the fitting accuracy of the response surface model. The multi-correlation index of the equivalent stress \( \sigma \) in the quadratic response model is 0.9887, the relation between the objective function \( m \) and the design variables contains only constants and cross terms theoretically. The multi-correlation index of mass \( m \) is infinitely close to 1, indicating that the quadratic response model fits well and can be used for optimization calculation instead of the actual model.

5. Multi-objective optimization

5.1. Optimization problems and mathematical models

The unit deck area of the rapidly helipad should be as large as possible, so as to reduce the assembling time and workload. As the horizontal length of the deck has been insured, its longitudinal length should be as large as possible. At the same time, the mass and equivalent stress of deck should be as small as possible. The mathematical model of the deck multi-objective optimization can be described as follows:
min \( m, \sigma \)

\[ \max (l_y) \]

s.t. \( m_X \leq m_U \)

\[ \sigma_X \leq \sigma_{vom} \]

\[ X_L \leq X \leq X_U \]

Where, \( m(X) \) is the mass of unit deck, \( \sigma(X) \) is the equivalent stress of deck, \( m_U \) is the upper mass limit of unit deck, \( \sigma_{vom} \) is the upper equivalent stress limit of deck, \( X = (l_y, h, D)^T \), \( X_L \) is the lower limit of design variables, \( X_U \) is the upper limit of design variables.

### 5.2. Multi-objective optimization

In multi-objective optimization, objective functions are constrained with each other. Thus, the optimization results are usually some non-inferior solutions which also named as Pareto sets. The optimization is just a initialy size design for the deck. Therefore, it’s carried out by Screen in AWB DX, and pareto feasible solutions[11] are shown in figure 10. In order to obtain a large domain, select 6 candidate points in 500 sample points.

![Figure 10. Pareto feasible solutions.](image)

Table 3 gives 6 design scheme corresponding to the feasible solutions, which can be selected for different design conditions and requirements.

| Serial number | Unit deck mass \( M \) (kg) | Equivalent stress \( \Sigma \) (MPa) | Longitudinal length \( l_y \) (m) |
|---------------|-----------------------------|------------------------------------|-------------------------------|
| 1             | 43.41                       | 12.54                              | 1.44                          |
| 2             | 50.19                       | 12.41                              | 1.49                          |
| 3             | 41.32                       | 12.20                              | 1.36                          |
| 4             | 48.46                       | 11.79                              | 1.41                          |
| 5             | 38.78                       | 12.47                              | 1.34                          |
| 6             | 49.83                       | 12.07                              | 1.43                          |

To further illustrate the effect of design parameters on objective function, partial sensitivity analysis charts are presented this paper. Figure 11 shows the effect of different design parameters on the maximum equivalent stress on the deck, as can be seen from the figure, the diameter of the connecting holes and the thickness of the deck have negative effects on the maximum equivalent stress, and the diameter of the connecting holes has the greatest influence on it.
In order to further study the effect of the diameter of the connecting holes on the maximum equivalent stress, the effect of the connecting holes’ diameter on the maximum equivalent stress is presented in figure 12. It can be seen from figure 12, as the diameter of the connecting holes increases gradually, the decrease of the maximum equivalent stress on deck gradually slows down. There is a roughly negative square correlation between the maximum equivalent stress and diameter of the connecting holes, which theoretical supports for the design of connecting holes.

Figure 13 shows the effect of different design parameters on the deck mass. Due to the existence of the connecting holes and the long holes, the longitudinal length and thickness do not have the same effect on the mass of deck. It is consistent with the theoretical results. Besides, the diameter of connecting holes has little effect on the mass of deck.

This paper chooses number 4 design scheme of feasible solutions, making round the design variables, take $D=36.0 \text{mm}$, $l=1.4 \text{m}$, $h=24.4 \text{mm}$, and the comparison with the result of pre-optimization is shown as Table 4. After optimization, on the basis of the original plane size, the mass of unit deck decreased by 2.46%, and the maximum equivalent stress decreased by 14.17%. Obviously,
it’s comprehensive performance was greatly improved, which could be used as a preliminary size design.

Table 4. Parameters comparison of the optimization.

| Parameters name                  | Before optimization | After optimization |
|----------------------------------|---------------------|--------------------|
| Mass of unit deck $m$(kg)        | 49.421              | 48.206             |
| Maximum equivalent stress $\sigma$(MPa) | 13.748              | 11.8               |
| Longitudinal length $l$(m)       | 1.4                 | 1.4                |

6. Conclusions

(1) In view of the most dangerous conditions of deck, the plane coordinate system and inequality group are established, which determines the plane size range of the deck. For two-wheeled helicopters, horizontal length of the deck has a small desirable range while longitudinal length has a wide desirable range.

(2) Deck made of High-density polyethylene (HDPE) has a good wheeled-bearing property, and equivalent strain could be controlled under the range of linear elastic strain while determining the thickness of the deck.

(3) For wheel-type helicopters, longitudinal length and thickness are the main factors affecting the mass of unit deck, and the thickness has a greater effect.

(4) Horizontal force has great effect on the connection of deck and designers can never neglect it. There is a roughly negative square correlation between the maximum equivalent stress and diameter of the connecting holes. In general design conditions, the diameter of the connecting holes has enough range of adjustment under the condition of allowable stress, which provides reference for design and adjustment of connectors.

(5) The design route and multi-objective optimization method adopted in this paper can identified the global pareto feasible solutions, which provides design reference for helicopter decks’ preliminary design of different design requirements and applications, and the design of high density polyethylene sheets.

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