Lightweight robust optimization design of mechanical claws of intelligent sanitation vehicle

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Abstract. As the dustbin grabbing device of the intelligent sanitation vehicle, the dimension errors caused by the manufacturing process should be considered in the lightweight design process of the mechanical claws. In this study, we used the mechanical claws as the carrier. The maximum deformation and the maximum equivalent stress of them were taken as the design responses and the plate thicknesses of different parts were taken as the design variables. A lightweight robust optimization design method for the mechanical claws was proposed by combining the optimal latin hypercube experimental design with high-precision Kriging approximate model and using Particle Swarm optimization (PSO) as the optimization solver. The optimization results show that this method has higher robustness than traditional deterministic methods although it has lower lightweight requirements. The final structural design of this study has higher advantages in preventing the fluctuation of uncertain parameters.

1. Introduction

There are many uncertain factors in the actual manufacturing process of mechanical claws, which cause the instability of their size parameters, while deterministic optimization often has the characteristics of optimal solution boundary[1]. It may cause the design variables or constraint functions to exceed the constraint boundary and the design will be unreliable or failure. Therefore, the influence of uncertainty factors should be fully considered in the lightweight design, and the optimization design based on uncertainty should be adopted. The 6σ robust optimization design is based on the robust optimization design based on tolerance model[2-5]. By introducing 6σ quality management and reliability optimization design, the σ level is taken as the quantitative description of quality state. It aims to minimize the target values and the standard deviation of each response as much as possible while ensuring the product quality at the mean value of 6σ. The reliability of the system is at least 99.9998%. Wang S. A[6] et al. used 6σ robust optimization method to design the soft magnetic composite material of the motor, which improved the performance of the motor; Bin Li[7] et al. used 6σ design to efficiently optimize the composite pressure hull of the underwater vehicle, and effectively reduce its weight.

In this paper, a robust lightweight optimization design method for the mechanical claws is proposed, which takes the mechanical claws who have been preliminarily optimized as the research object, considers the robust requirements and lightweight objectives of the design, combines the optimal latin hypercube experimental design and high-precision Kriging approximate model, and uses PSO as the optimization solver.
2. Robust optimization design theory based on Kriging

2.1. The basic theory of robust optimization

Robust optimization is to find the "flat" area in the design space, minimize is the fluctuation of output response caused by uncertain input variables, and meet the reliability probability of quality constraints. The principle of robust optimization is shown in Figure 1. If the influence of uncertain factors of input variables on the performance is not considered, point a is the optimal solution of deterministic optimization, when the input variable changes $\Delta x$, the objective function changes $\Delta f_a$, and the design is beyond the quality constraints. The point b is the best point of reliability, when the input variable changes $\Delta x$, the objective function changes $\Delta f_b$. Although the design does not exceed the constraint, the performance fluctuates greatly, that is, the design point is more sensitive, poor robustness. And the point c is the best point of robustness, when the input variable changes $\Delta x$, the objective function changes $\Delta f_c$. The design does not exceed the constraints, and the design point is less sensitive, good robustness.

2.2. The basic theory of Kriging approximate model

Kriging approximate modeling technology is an unbiased estimation model with minimum estimation variance. This method can describe the highly nonlinear process, make the target responses smooth, remove the numerical noise, and greatly improve the efficiency of optimization design.

Kriging approximate model is composed of global model and local deviation, which can be expressed as:

$$ y(x) = f(x) + z(x) $$

Where, $y(x)$ is the approximate response value of the target response. $f(x) = \{f_1(x), ..., f_p(x)\}$, which is the regression basis function of approximate model. $\beta = \{\beta_1, ..., \beta_p\}$, which is the regression coefficient. $z(x)$ is a stochastic process with zero mean, $\theta^2$ variance and non-zero covariance.

The samples used to construct the Kriging approximate model can be obtained by the optimal latin hypercube experimental design method. Based on the Latin square experimental design, it uses the optimization algorithm to make the sampling points evenly distributed in the design space as much as possible. For non-linear problems, it can greatly reduce the size of experimental design samples.

3. Mechanical structure design and finite element modeling

3.1. Mechanical structure design

There are mainly two types of mechanical claws, linear and arced, while the domestic outdoor dustbins are mostly rectangular. The contact surface between linear mechanical claws and a dustbin is relatively large, and the fit tolerance between the two is difficult to guarantee, which may lead to over positioning and complex stress situation. While the contact point between a arc mechanical claw and a dustbin is only a point, and the force is clear. In addition, arc mechanical claws have the effect of squeezing the
dustbin because of its radian when clamping, while the linear mechanical claw is easy to push it out, as shown in Figure 2(a) and (b).

Arc mechanical claws can adjust the dustbin in any position to make it right, so as to facilitate the clamping and lifting. The position adjustment process is shown in Figure 2(c). It can be seen that arc mechanical claws are more suitable for rectangular dustbins.

![Figure 2. Schematic diagrams of mechanical claws exerting force.](image)

The mechanical claws are designed in Solidworks and the Hypermesh is used for topology optimization preliminary. The structure of the left and right mechanical claws are shown in Figure 3.

![Figure 3. 3D model of mechanical claws.](image)

### 3.2. The finite element model

Outdoor dustbins are mainly available in 120L and 240L specifications. Because the loading weight of a 240L dustbin is larger, the force exerted on mechanical claws is worse when being clamped and moved. Therefore, the process of mechanical claws grabbing a 240L dustbin is selected as the optimal design condition. Import the 3D models of mechanical claws into Hypermesh, set their material to be carbon steel, yield strength $\sigma_y = 355MPa$, density $\rho = 7850kg/m^3$, and elastic modulus $E = 210GPa$. And set the grid size to 2mm. According to the mechanical knowledge, positive pressures of 1660N are applied on the inner side of the outer end of the mechanical claws, which are evenly distributed along the normal direction of the contact surface, and static friction forces of 903N are applied at the same stress position, which are vertically and downward evenly distributed with the positive pressures direction. The force areas of the left and right mechanical claws are 600mm$^2$ and 540mm$^2$. Fixed constraints are applied to another ends, and the finite element models for static analysis of the mechanical claws are shown in Figure 4.

![Figure 4. The finite element models of the mechanical claws.](image)

According to the actual engineering experience, we set the safety of strength to be 1.2 and the safety of the static stiffness to be 1.1, and the allowable stress is:

$$\sigma = \frac{\sigma_y}{1.2} = 296MPa$$  \hspace{1cm} (2)

If the design value $d_s$ of deformation is 10 mm, the allowable deformation is:

$$[d_s] = \frac{d_s}{1.1} = 9mm$$  \hspace{1cm} (3)

The equivalent stress nephograms of the mechanical claws obtained by Hypermesh simulation are shown in Figure 5, and the displacement nephograms are shown in Figure 6. It can be seen from Figure...
that the maximum equivalent stresses of the left and right mechanical claws are 218.7MPa and 184.4MPa respectively, which are less than the allowable stress of the material, and the equivalent stresses of other parts are basically less than 100Mpa. And it can be seen from Figure 6 that the maximum deformations of the left and right mechanical claws are 5.8mm and 5.9mm respectively, which are less than the allowable deformation. Therefore, the structural performance indicators of the mechanical claws are all less than their performance limits, and the mechanical claws have considerable margins of lightweight.

4. The lightweight optimization process

4.1. The description of optimization problem

According to the engineering requirements, the length and width of the mechanical claws are set as the fixed value. The weight should be minimized as far as possible while meeting the requirements of strength and rigidity. Therefore, the plate thicknesses of different parts are selected as the design variables, which are the left mechanical claw: two fingers $p_1$, box $p_2$, box rib $p_3$, main body $p_4$, main body rib $p_5$, and the right mechanical claw: vertical plate $p_6$, flat plate $p_7$ and rib $p_8$. According to the engineering experience and relevant literature, the initial values of the eight design variables are set to 5mm, and their value ranges are set to $[3,8]$ (mm), the design variables are subject to normal distribution.

To establish the Kriging approximate model reflecting the performance index, weight and design variables, the optimal Latin hypercube experimental design method is used to collect sampling points, and maximum equivalent stress, maximum deformation and weight corresponding to sampling points are obtained through finite element numerical simulation.

4.2. The optimization model

Firstly, in order to meet the requirements of lightweight design, taking the minimum weight of the mechanical claws as the objective, the maximum equivalent stress and maximum deformation are set as the constraint conditions, and PSO is used to optimize the design. The mathematical model of deterministic optimization design constructed in this paper as follows:

$$
\begin{align*}
\min m \\
st. \delta_{\text{max}} & \leq 296 \\
& d_{\text{max}} \leq 9 \\
3 \leq p_i \leq 8, \ i = 1,2, \ldots, 8
\end{align*}
$$

(4)

Compared with the above method, the uncertainty of design parameters are considered in the robust optimization process. The objective of this study is to minimize the mean value and standard deviation of the weight, the standard deviations of the maximum equivalent stress and the maximum deformation. The constraint condition is that the mean values of the maximum equivalent stress and the maximum deformation, and that the design variables are far away from the constraint boundary and reach the 6σ level. After normalization, the lightweight design based on 6σ robustness is constructed. The mathematical model is as follows:
\[
\begin{align*}
\min & \quad \frac{\mu(m)}{8.61} + \frac{\sigma(m)}{8.61} + \frac{\sigma(d_{\text{max}})}{9} + \frac{\sigma(\delta_{\text{max}})}{296} \\
\text{s. t.} & \quad \mu(\delta_{\text{max}}) + 6\sigma(\delta_{\text{max}}) \leq 296 \\
& \quad \mu(d_{\text{max}}) + 6\sigma(d_{\text{max}}) \leq 9 \\
& \quad 3 + 6\sigma(p_i) \leq p_i \leq 8 - 6\sigma(p_i), i = 1, 2, \ldots, 8
\end{align*}
\]

(5)

Where, \(\mu(m)\), \(\mu(\delta_{\text{max}})\) and \(\mu(d_{\text{max}})\) are the mean values of the weight, the maximum equivalent stress and the maximum deformation respectively. \(\sigma(m)\), \(\sigma(\delta_{\text{max}})\) and \(\sigma(d_{\text{max}})\) are the standard deviations of them. And \(\sigma(p_i)(i = 1, 2, \ldots, 8)\) are the standard deviations of design variables. The primary purpose of the 6σ robust lightweight design of the mechanical claws is to give full play to the lightweight potential and minimize the weight. In addition, it is necessary to reduce the standard deviation of each performance index to ensure that each performance index is not sensitive to the change of design variables. And it is important to ensure that the fluctuation of weight is small and the weight consistency is maintained as far as possible.

4.3. The optimization design results and comparative analysis

| Table 1. The optimization results of the left mechanical claw | Table 2. The optimization results of the right mechanical claw |
|-------------------------------------------------------------|-------------------------------------------------------------|
| design variables   | deterministic optimization | robust optimization | design variables | deterministic optimization | robust optimization |
| \(p_i\) (mm)       | 3.0                         | 4.2                  | \(p_i\) (mm)     | 3.7                         | 6.4                  |
| \(p_i\) (mm)       | 4.2                         | 6.6                  | \(p_i\) (mm)     | 3.7                         | 6.5                  |
| \(p_i\) (mm)       | 3.3                         | 6.6                  | \(p_i\) (mm)     | 3.8                         | 6.5                  |
| \(p_i\) (mm)       | 7.5                         | 5.9                  | \(\mu(d_{\text{max}})\) (mm) | 8.1                         | 4.4                  |
| \(p_i\) (mm)       | 3.6                         | 4.7                  | \(\mu(\delta_{\text{max}})\) (MPa) | 295                         | 151                  |
| \(\mu(m)\) (kg)   | 5.5                         | 8.3                  | \(\mu(m)\) (kg)  | 4.2                         | 7.2                  |
| \(\sigma(d_{\text{max}})\) (mm) | 0.032                       | 0.019                | \(\sigma(d_{\text{max}})\) (mm) | 0.030                       | 0.017                |
| \(\sigma(\delta_{\text{max}})\) (MPa) | 1.2                         | 0.5                  | \(\sigma(\delta_{\text{max}})\) (MPa) | 0.9                         | 0.5                  |
| \(\sigma(m)\) (kg) | 0.0015                      | 0.0012               | \(\sigma(m)\) (kg) | 0.0014                      | 0.0012                |

From the data in Table 1 and Table 2, it can be seen that from the perspective of structural performance, compared with deterministic optimization, 6σ robust optimization design makes the maximum equivalent stress and maximum deformation of the mechanical claws decrease significantly, enhancing the strength and stiffness of the structure. As for robustness, it makes the standard deviations of the maximum equivalent stress, the maximum deformation and the weight of the mechanical claws decrease significantly, which not only improves the consistency of weight, but also reduces the sensitivity of the maximum equivalent stress and the maximum deformation to the variation of design variables, and improves the robustness of stiffness and strength. And from the lightweight point of view, the weight of the mechanical claws obtained by 6σ robust optimization design is improved a little, which is more conservative than the deterministic optimization, but it has higher stability when considering the disturbance caused by size uncertainty.

5. Conclusion

By considering the specifications of outdoor dustbins, mechanical claws structure suitable for clamping different sizes of dustbins is designed. To further improve the lightweight characteristics of the mechanical claws, we take the maximum deformation and the maximum equivalent stress of them as the design responses and take the plate thicknesses at different parts of them as the design variables. Combining the optimal Latin hypercube experimental design and the high-precision Kriging approximate model, and using PSO as the optimization solver, the optimal design method of lightweight of mechanical claws of
intelligent sanitation vehicle is proposed. The optimization results show that the robust lightweight optimization method has higher robustness than traditional deterministic methods although it has lower lightweight requirements. The final structural design of this study has higher advantages in preventing the fluctuation of uncertain parameters.

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