Study on Structure Optimization Design for Outrigger of In-situ Slewing Device

Huifu Jiang¹, Guosheng Zhang¹*, Jiaxing Zhang², Linbo Zhang³

¹ Research Institute of Highway Ministry of Transport, Beijing, 100088, China
² College of Mechanical Engineering, Shenyang University of Technology, Shenyang, Liaoning, 110870, China
³ China Automotive Technology & Research Center Co. Ltd, Tianjin, 300300, China

*Corresponding author’s e-mail: Huifu.jiang@rioh.cn

Abstract: To solve the problem of insufficient turning radius for heavy-duty wreckers in narrow and congested road environment, this paper designed a new type of in-situ slewing device, and conducted a finite element simulation analysis on it. On this basis, by combining the optimization theory, this paper further optimized the structure of in-situ slewing device by using three different optimization design methods, including screening method, nonlinear second-order Lagrange method and quadratic integer sequence algorithm. The total weight loss of outrigger structure was 69.96 kilogram, the weight-loss ratio is equal to 7.34%. These results prove that the goal of structural optimization design has been achieved.

1. The introduction
After the traffic accident has happened, the failure to carry out fast and efficient obstacle clearance rescue will affect the safety and smoothness of road traffic, reduce the transportation efficiency, cause additional energy consumption and environmental pollution, and even cause secondary accidents due to the delay or improper operation of block removal and rescue, result in more casualties.

Current road block removal and rescue of traffic accident, especially under various complex road environment such as tunnels, overpasses, mountain road and so on, the narrow operation space leads to the failure of road block removal and rescue. It is urgent for researchers and engineers to developed a new type of in-situ slewing device to adapt to the educational development of road block removal and rescue of traffic accident.

2. Design of in-situ slewing device
The in-situ slewing device is composed of outrigger, outrigger connecting frame, hydraulic motor, hydraulic cylinder, roller guide rail and other components. One side of outrigger connecting frame is welded with the outrigger and the other side is welded with the subframe. The outrigger has an inner sleeve and an outer sleeve, and there relative motion is accommodated by the telescopic cylinder. The lower part of inner sleeve is connected with the roller, which could move along the guide rail powered by the hydraulic motor connected with it. When the guide rail is lowered and the wrecker body is lifted off the ground by outrigger, the wrecker could rotate 360° on the spot with the roller powered by hydraulic motor.
Figure 1. In-situ slewing device

The basic parameters are shown in Table 1.

| Project                        | Unit | Number |
|--------------------------------|------|--------|
| Number of outriggers          |      | 4      |
| Number of hydraulic motors    |      | 2      |
| In-situ slewing angle         |      | 360    |
| Inner meridian of guide rail  | mm   | 2290   |
| Extension stroke of outrigger | mm   | 510    |
| Maximum lifting height        | mm   | 230    |

The complete vehicle schematic diagram of in-situ slewing device is shown in Figure 2. This device could lift up and rotate the wrecker body. The rotary diameter is about 11.5 meters, which is equal to the diagonal length of wrecker body, and far less than the minimum turning diameter of 21.6 meters without in-situ slewing device. Therefore, this device could solve the turning problem of heavy-duty wrecker in narrow and congested road environment, and provide a good solution for improving rescue efficiency.

Figure 2. Full-vehicle schematic diagram of in-situ slewing device

3. Establishment and analysis of outrigger structure model

Because the main force components of in-situ slewing device are outriggers, and the four outriggers are arranged in 90° order on the circumference of guide rail, these four outriggers have same force characteristics, so only one geometric model of outrigger should be established. This geometric model was established by the software SolidWorks and output in .igs or .stp format, and then imported into
the finite element pre-processing software Hypermesh to complete grid division. The unit size of this finite element model is between 10 mm to 20 mm. This model has 26940 nodes and 14374 units, including 13031 hexahedral units and 1316 wedge-shaped units, as shown in figure 3.

Figure 3. Finite element model of outrigger

When the in-situ slewing device is working, the four outriggers lift the wrecker off the ground and carry the full weight of it. The outrigger connecting frame is welded with subframe, the weight is transferred to outriggers through the side plates of connecting frame. The roller bracket connects outrigger with roller with pin shaft, and the pin hole of roller bracket can be seem as a fixed constraint. By calculation, the structure strength of outrigger is shown in figure 4.

Figure 4. Stress nephogram of single outrigger

The calculation results show that the maximum stress of 360° slewing mechanism is located in the joint of outrigger and outrigger bracket, the peak value is only 90.72 MPa, which is far less than the yield limit of 345 MPa. It can be seen, the structure of outrigger greatly meets the strength requirement. But there is also a lot of room for structural optimization.

4. Structure optimization design of outrigger

4.1 Steps of structural optimization design

This paper studied the structure optimization design of outrigger of wrecker in-situ slewing device from the perspective of structural size optimization.

Step 1: Establish the geometric model of outriggers by using SolidWorks, and define all parametric variables in it;

Step 2: Import the geometric model of outriggers into Workbench through its CAD interface, add
Step 3: Set the constraints, objective function and optimization method of analysis project;
Step 4: Carry out structural optimization design;
Step 5: View the analysis results and generate an analysis report

4.2 Parameters definition

4.2.1 Design variables. This paper chose the thickness of eight components as design variables of structure optimization, including the upper and lower plates of outrigger connecting frame, the outer and inner walls of outer sleeve, the outer and inner walls of inner sleeve, and the upper and side plates of roller bracket. The thickness were respectively defined as DS_H1, DS_H2, …, DS_H8, as shown in figure 5. The initial value and value range of each variable are shown in Table 2. These eight variables were respectively established as P1, P2, …, P8 in Design Exploration.

![Figure 5. Define parameters](image)

Table 2. Design variables

| component name                     | design variables | initial value(mm) | Minimum (mm) | Maximum(mm) |
|------------------------------------|------------------|-------------------|--------------|-------------|
| outrigger connecting frame         |                  |                   |              |             |
| upper plate                        | DS_H1            | 12                | 6            | 16          |
| lower plate                        | DS_H2            | 12                | 6            | 16          |
| outer sleeve outer wall            | DS_H3            | 8                 | 6            | 10          |
| outer sleeve inner wall            | DS_H4            | 8                 | 6            | 10          |
| inner sleeve outer wall            | DS_H5            | 8                 | 6            | 10          |
| inner sleeve inner wall            | DS_H6            | 8                 | 6            | 10          |
| roller bracket upper plate         | DS_H7            | 30                | 20           | 35          |
| roller bracket side plate          | DS_H8            | 40                | 30           | 45          |

4.2.2 Constraints. The purpose of optimization design is minimizing the weight of component on the premise of meeting the yield strength of material. The outrigger connecting frame and rest components are made from different materials, and their yield strength is not the same. The constraints of design variables are shown as follows:

\[
\begin{align*}
0 & < P9 < 700 \\
0 & < P10 < 345
\end{align*}
\]

In the equation, variable \( P9 \) is defined as the stress of outrigger connecting frame, and variable \( P10 \) is the stress of rest component.
4.2.3 **Objective function.** The objective function of optimization design for weight reduction of outriggers of in-situ slewing device is the total mass of outriggers:

$$\min M = \rho \sum V$$

In this equation, $M$ is the total weight of outriggers; $\rho$ is the density of material used for outriggers; $V$ is the volume of component.

The global variable $P11$ was established in Design Exploration, the total weight of outriggers was extracted and assigned to the variable $P11$. Finally, $P11$ represents the objective function.

The setting of design variables, constraints and objective function are shown in Figures 6-7.

![Figure 6. Setting of design variables](image)

![Figure 7. Setting of constraints and objective function](image)

4.2.4 **Optimization design method.** In the optimization design method for outriggers, the input parameters are the thickness of component plates, which are continuous variables. The output parameters are the stress and total mass of outriggers. The magnitude of stress is limited by constraints. Minimizing the total mass is the final design goal. Hence, this method is a single-objective optimization of output parameters. This research adopted the screening method, nonlinear second-order Lagrange method and integer sequence quadratic algorithm to solve this optimization problem, and determine the optimal design by comparing the calculation results of different solving methods.

4.3 **Analysis of optimization results.**

The nonlinear second-order Lagrange method generated three sets of optimal value after iterating 3 times through each input parameter; Screening method defined a total of 100 design points, and generated five sets of optimal value after iterating 3 times through each design point; Integer sequence
quadratic algorithm defined 93 design points and obtained five sets of optimal values after calculation. Finally, a data comparison could be formed by filtrating the optimal values obtained from these three methods, as shown in Table 3. The table shows that all thickness values of plates generated by integer sequence quadratic algorithm are decreased, $P_{11}$ reaches the minimum value, $P_9$ is lower than 700, and $P_{10}$ is lower than 345. The results meet the requirements of optimization design, so this group of results is selected as the optimal design scheme.

Table 3. Contrast between three optimization design methods

| Parameters | Unit | Nonlinear second-order Lagrange method | Screening method | Integer sequence quadratic algorithm |
|------------|------|----------------------------------------|-----------------|--------------------------------------|
| DS_H1      | mm   | 6.366                                  | 11.751          | 6                                    |
| DS_H2      |      | 6.655                                  | 11.788          | 6                                    |
| DS_H3      |      | 6.305                                  | 7.710           | 6                                    |
| DS_H4      |      | 6.525                                  | 7.707           | 6                                    |
| DS_H5      |      | 6.769                                  | 7.756           | 6                                    |
| DS_H6      |      | 6.177                                  | 7.769           | 6                                    |
| DS_H7      |      | 20.419                                 | 29.667          | 20                                   |
| DS_H8      |      | 30.171                                 | 39.088          | 30                                   |
| $P_9$      | MPa  | 124.82                                 | 91.99           | 127.43                               |
| $P_{10}$   | kg   | 253.67                                 | 116.03          | 301.39                               |
| $P_{11}$   |      | 224.15                                 | 232.45          | 220.75                               |

The parameters of outrigger were modified in SolidWorks and re-calculated after being imported into Workbench, the maximum stress of optimized outrigger appeared at the contact point between inner sleeve and the roller bracket, its value is 321.06MPa, which has a certain error with the maximum stress of 301.39MPa obtained by optimization design. But this maximum stress is not more than the yield limit of materials equals to 345MPa, the outrigger structure is safe and reliable.

The weight of front outrigger before optimization is 238.24 kg, the weight of rear outrigger after optimization is 220.75 kg, the total weight reduction of four outriggers is 69.96kg, and the reduction rate is 7.34%. The results show that the optimization goal has been achieved.

5. Conclusions

This paper optimized the structure of the outrigger of in-situ slewing device based on the optimization design theory, designed and calculated by utilizing the screening method, non-linear second-order Lagrange method and integer sequence quadratic algorithm, and finally found out the optimal designing scheme through comparison of optimization results generated by three different methods. The outrigger model was modified according to the optimal designing scheme, its stress calculation results show that the maximum stress of optimized structure is not more than the yield limit of material, the optimal designing scheme is feasible. The comparison of weight of outrigger before and after optimization shows that that the total weight reduction could reach 69.96kg, the reduction rate is 7.34%, and the optimization goal is achieved.

Acknowledgments

This research was supported by the National Key Research and Development Program of China (No.2016YFC0802706).

References

[1] Kulka, J., Mantic, M., Fedorko, G., et al. (2016) Analysis of crane track degradation due to operation. Thin-Walled Structures, 59(1): 384-395.
[2] Celik, H.K., Rennie, A.E.W., Akinci, I. (2017) Design and structural optimisation of a tractor mounted telescopic boom crane. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 39(3): 909-924.
[3] Qian, J.M., Jiang, X.H., Zhong, X.D., et al. (2006) Discussion on Contact Analysis Based on ANSYS Software. Coal Mine Machinery, 07: 62-64.
[4] Mile, S., Milomir, G., Goran, P. (2014) Stress Analysis in Contact Zone Between the Segments of Telescopic Booms of Hydraulic Truck Cranes. Thin-Walled Structures, 85: 332-340.
[5] Chen, C.J., Mohamnlad, U.(2001) Desing Optimization for Automotive Application. Vehicle Design, 25(2): 126-139.
[6] Srinivas, K., Jaroslwa, S.(2001) Multidisciplinary Design Optimization some Formal Method, Framework Requirements and application to Vehicle Design. Vehicle Design, 25(2): 3-23.
[7] Zhang, G.S.(2017) Quality Education Textbook for Rescue Workers in Road Block Removal (Equipment Part). China Communications Press, Beijing.