Ma *et al. Chin. J. Mech. Eng.* (2018) 31:42
https://doi.org/10.1186/s10033-018-0236-3

Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE

Open Access

Light-Weight Design Method for Force-Performance-Structure of Complex Structural Part Based Co-operative Optimization

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Abstract

A light-weight design method of integrated structural topology and size co-optimization for the force-performance-structure of complex structural parts is presented in this paper. Firstly, the supporting function of a complex structural part is built to map the force transmission, where the force exerted areas and constraints are considered as connecting structure and the structural configuration, to determine the part performance as well as the force routines. Then the connecting structure design model, aiming to optimize the static and dynamic performances on connection configuration, is developed, and the optimum design of the characteristic parameters is carried out by means of the collaborative optimization method, namely, the integrated structural topology optimization and size optimization. In this design model, the objective is to maximize the connecting stiffness. Based on the relationship between the force and the structural configuration of a part, the optimal force transmission routine that can meet the performance requirements is obtained using the structural topology optimization technology. Accordingly, the light-weight design of conceptual configuration for complex parts under multi-objective and multi-condition can be realized. Finally, based on the proposed collaborative optimization design method, the optimal performance and optimal structure of the complex parts with light weight are realized, and the reasonable structural unit configuration and size characteristic parameters are obtained. A bed structure of gantry-type machining center is designed by using the proposed light-weight structure design method in this paper, as an illustrative example. The bed after the design optimization is lighter 8% than original one, and the rail deformation is reduced by 5%. Moreover, the lightweight design of the bed is achieved with enhanced performance to show the effectiveness of the proposed method.

Keywords: Light-weight design, Part structure, Topology optimization, Size optimization, Force, Performance

1 Introduction

Parts as supporting structure with heavy and complex structure in machine, are known as rack parts or complex parts, such as base, box [1]. The main functions of such parts in the machine are to overcome the workloads and their own gravities, and to transmit the loads and forces to foundations. The shape and size of the parts structure directly affects the static and dynamic performance of the machine [2]. Due to the diversity of machine configuration and the working load, the load and structure of the parts are complicated and the structural design with optimal performance is difficult. Therefore, it is very important to develop the high performance, light weight and low cost structure design method of rack parts.

It is a big challenge to reduce part weight without decreasing its performance. Many scholars have conducted the research on this topic. Nguyen et al. [3] presented a heuristic optimization method in combination with additive manufacturing for synthesizing large mesoscale lattice structure of complex shaped parts. Park et al. [4] proposed a weight reduction design process of suspension link, which was based on the variation of von-Mises stress contour by substituting an aluminum alloys (A356) having tensile strength of 310 MPa grade instead of STKM11A steels. Raj et al. [5] evaluated the

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performance of two different design configurations of a bimetal brake drum by means of dynamometer test in order to improve heat dissipation and to reduce its weight. Zhang et al. [6] used the orthogonal experiment method to optimize the structure of ship unloader and realized the light weight design. Tan et al. [7] proposed a linkage-based evolutionary design method of the part structure to solve the unified representation problem between the geometric elements and the design intent attached to the geometric elements. Zhang et al. [8] established the design guidelines of equivalent static toughness for using aluminum hubs and rims instead of the original steel components to reduce the weight of action components of heavy vehicle. Qu et al. [9] proposed an algorithm by combining ant colony algorithm with a mutation-based local search and used for a real crane metal structure optimal design.

In recent years, many scholars have applied the finite element analysis method and structural topology optimization technology to design the structures of mechanical products such as machine tools, automobiles and airplanes for reducing the weight and improving the performance of products [10]. The topology optimization technology applied to the machine tools can reduce the weight, improve its stiffness and frequency [11]. Hassan et al. [12] applied topology optimization technique for the design optimization of load-bearing elastic structures for the metallic antenna design. Duysinx and Bendsøe [13] introduced an extension of current technologies for topology optimization of continuum structures which allows for treating local stress criteria. Petersson et al. [14] considered the problem of minimum compliance topology optimization of an elastic continuum. Aage et al. [15] proposed a fully parallel topology optimization framework implemented in C++ to realize the structural optimization. Lan et al. [16] used finite element and topology to investigate the car body's multi-load conditions and made the structure more reasonable. Liu et al. [17] used topological method to achieve the light-weight design of unmanned aerial vehicle landing gear outer cylinder pillar. Chen et al. [18] proposed a dynamic topology multi-force particle swarm optimization algorithm in order to get better performance. Xu [19] applied the guide weight method into the topology optimization used for the arm of flight simulator. These research results provide important basis and reference for the study of complex parts structural design methods.

In this paper, a complex part structure design method of force-performance-structure is proposed, by analyzing the internal relationships between load and constraint characteristics, force and structure, performance and structure of the part. And the structural light-weight design optimization of static and dynamic performance of the part is realized through the co-operative optimization by integrating structural topology optimization and size optimization.

2 Optimization Models of a Part

This section aims to build the topology and size cooperative optimization design models with the force-performance-structure, to realize the light-weight design of a complex part structure and size which can meet the multi-performance requirements. It is noteworthy that the design models include both a mathematical optimization model and a physical optimization model. Taking the static and dynamic performance as objective function, the light weight as constraint and the material density or the feature size as optimization variables, the mathematical optimization model is established. Moreover, the physical optimization model with loads, constraints, optimal design domains, non-optimal design domains is developed.

2.1 Mathematical Optimization Model

2.1.1 Mathematical Optimization Model of Structural Configuration

Topology optimization is the process of determining the connectivity, shape, and location of voids in given design domains [20]. For a complex part design, the goal of the structure optimization design is to achieve a light weight structure configuration with optimal static and dynamic performance [21]. As the variations of working conditions of the part directly affect the optimization design results, the static and dynamic combined strain energy under multiple conditions should be considered for the structural optimization design, sequentially, the optimal mathematical model is expressed as below:

$$\begin{cases} \min \ S(\boldsymbol{x}) = \sum \omega_i \boldsymbol{\mu}_i(\boldsymbol{x})^{\mathrm{T}} \boldsymbol{K} \boldsymbol{\mu}_i(\boldsymbol{x}) + NORM \dfrac{\sum \omega_j / \lambda_j(\boldsymbol{x})}{\sum \omega_j}, \\ \text{s.t.,} \begin{cases} V_i(\boldsymbol{x})/V_0 \leq \boldsymbol{\Delta}, \\ 0 \leq x_k \leq 1, \quad k = 1, 2, \ldots, N, \end{cases} \end{cases} \tag{1}$$

where $S(\boldsymbol{x})$ is the weighted strain energy, ω_i and ω_j are the weighted coefficient of the ith operating condition of strain energy and dynamic characteristic, and $\boldsymbol{\mu}_i(\boldsymbol{x})$ is the node displacement vector of the ith operating condition, respectively. Moreover, $\boldsymbol{K}$ is the system stiffness matrix, $\lambda_j(\boldsymbol{x})$ is the jth order eigenvalue, *NOMR* is the correction coefficient to correct the strain energy and eigenvalue contribution degree, $\boldsymbol{V}_i(\boldsymbol{x})$ is the total volume after optimization, $\boldsymbol{V}_0$ is the initial volume, $\boldsymbol{\Delta}$ is the optimization volume ratio constraint, generally taken $0-1$, x_k is the design variable of material density, varying between 0 and 1.

2.1.2 Mathematical Optimization Model of Structural Feature Sizes

The optimal structural feature sizes of a part can be determined after its structural configuration design, to meet the final performance requirements, which are related to the stiffness, strength and weight [22]. Considering the stiffness, strength and weight of the part, the mathematical model of multi-objective size optimization is formulated as

$$\begin{cases} \min\limits_{X}(D_1(\boldsymbol{X}),\ldots,D_i(\boldsymbol{X}),D_p(\boldsymbol{X})),\ i=1,2,3,\ldots,p, \\ \text{s.t.,} f_1(\boldsymbol{X}) \geq f, \\ \boldsymbol{X}=(X_1,X_2,X_i,\ldots,X_n),\ i=1,2,3,\ldots,n, \end{cases} \tag{2}$$

where $D_i(\boldsymbol{X})$ is the optimization objective, $f_1(\boldsymbol{X})$ is the constraint function including the maximum stress and strain of a part, f is the constraint boundary of the constraint function, X_i is the optimization variables of structural feature size, respectively.

In this paper, the second order response surface method [23] is used to construct the part approximation model to solve the objective function and the constraint function. The established structural size optimization model by using the second order response surface method is given by

$$D_k(\boldsymbol{X}) = a_0 + \sum_{i=1}^{n} b_i\boldsymbol{X}_i + \sum_{i=1}^{n} c_{ii}\boldsymbol{X}_i^2 + \sum_{ij(i \prec j)} c_{ij}\boldsymbol{X}_i\boldsymbol{X}_j, \tag{3}$$

where $\boldsymbol{X}_i$ and $\boldsymbol{X}_j$ are the input feature size optimization variables, a_0, b_i, c_{ii} and c_{ij} are the polynomial coefficients. In order to reduce the model error, the least squares method is used to regress the coefficients.

2.2 Physical Optimization Model

Considering the functions, connections, geometry, overall size characteristics, loads, constraints and optimization design interval of a part, the physical optimization model is built, including geometric model, design domains, loads and constraints equivalence.

The geometric model is constructed, which follows the functional rule, geometry rule and size rule in this paper. Functional rule is to determine the basic structure based on support, installation, auxiliary operation and other functional constraints of the part. The geometry rule is that the part should be made up of basic geometry structures or their combination, such as revolving body and non-swivel body of rectangular parallelepiped. The size rule is to determine the geometric sizes according to the machine-related parameters, the movement space of the adjacent parts and the positions of the loads. The design domains mean the variable areas of model during the topology optimization process. The non-design domains mean the non-variable areas of model to satisfy some installation requirements, such as moving contact surfaces, connection structures of the part, etc.

A complex part often works under multi-condition, of which the types, directions, magnitude, locations and numbers of working loads will vary correspondingly during operation. Theoretically, the working loads should be calculated using the load spectrum, however, the actual load spectrum is often unknown. Therefore, the working loads of multi-condition is weighted equivalent performed based on dangerous conditions, typical conditions and the working frequency. The constraints on the connection surfaces constrain the motion and deformation of a part called degree of freedom constraint and stiffness constraint respectively. According to the types of connection, the mobility constraints are classified into movable connection and stable connection constraints [24]. Furthermore, the stiffness characteristics of a part are difficult to accurately solve due to plenty of affecting factors. Therefore, it is important that the constrained degree of freedom and stiffness equivalent rules are simplified to establish constraint equivalent models for simulating the effect of the motion and deformation. The degree of freedom equivalent rule is to determine the number and direction of the constrained motion based on the type of connection. The stiffness equivalent rule is to equal the stiffness characteristic of actual joint surface by using spring equivalent and contact equivalent method.

Taking a gantry-type machining center bed as an example, two dangerous conditions and a typical working condition are considered. The loads are applied to the joint of the guide rail and the bearing seat. Considering the constrained bottom area of the bed, the physical optimization model of the bolt connection structure is shown in Figure 1.

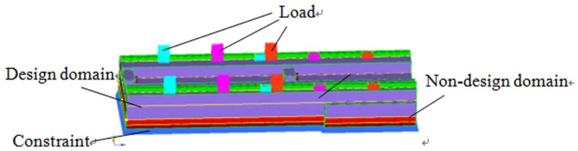


Figure 1 Physical optimization model of bed bolt connection structure

3 Force-Performance-Structure Light-Weight Design of a Part

One of the main function of a rack part is transferring the working load to the joint constraint position [25], referred to the force transmission. The working load acting domain and the constraint domain correspond to the joint surface of the part, mapped as the connection structure. The transmitting routine of the force is mapped to the structural configuration of the part connecting the load with the constraint, which is grouped into the main structure and the sub-structure. The main structure is the main force routine, and the sub-structure and its combination is commonly used auxiliary structure adhered to the main structure to further improve the part performance, which is called the structural unit in this article. On the other hand, the part structure significantly determines the part performance. Based on the mapping relationship between the force-structure and performance-structure, a co-operative optimization design method for structure light-weight, based on structural topology optimization and size optimization, is proposed, for which the flowchart is shown in Figure 2 (Additional file 1).

3.1 Connection Constraint-Performance-Structure Design

The complex part is generally connected to at least two other parts, forming the load and the restraint connection structure. The load and constraint position, the connection feature sizes directly affect the structural configuration of the part obtained by the topology optimization, and more importantly, the part performance [26]. Structural topology optimization and size optimization are used to optimize the performance of the connection structure and the main feature sizes.

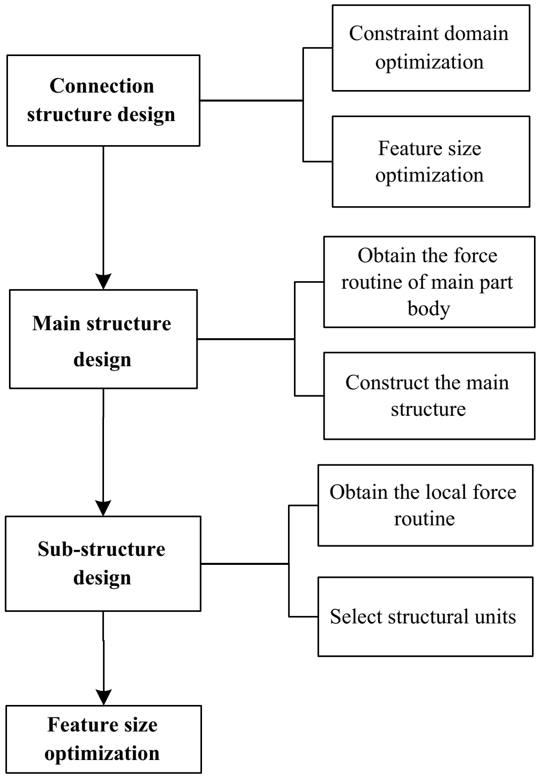


Figure 2 Co-operative optimization design method for structure light-weight

3.1.1 Connection Constraint Domain Optimization Design

The optimization model is constructed by using the method described in Section 2, and the topology optimization method can be used to obtain the constraint domain with the optimal performance under multi-condition [27]. The focus of the method is to set the optimal design domain between the main body of the part and the connection surface in the physical optimization model.

Take a machine tool spindle box as an example, the design of the connection constraint domain is obtained based on the above method, as shown in Figure 3. Due to the complexity for the working conditions of the part, the connection constraint domain will change with working conditions. In order to measure the effect of load, the connection constraint domain is optimized by varying the load value ratio $\boldsymbol{F}_x/\boldsymbol{F}_y$ in the x and y direction, as shown in Figure 4.

As seen from Figure 4, with the increasing load value ratio, the connection constraint domain is evenly distributed around the two sides along the x direction. From the above, the design of connection constraint domain of a part needs to completely consider multi-condition loads.

3.1.2 Feature Sizes Optimization of Connection Structure

In order to improve the connection structure performance, the size optimization method is used to determine the optimal feature parameters of joint structure, and to provide reasonable constraint position for the optimization design of the following main structural configuration.

In general, due to the variations of the connection type and the structure configuration, there exist many kinds of feature sizes [28]. It is of importance to select the main feature sizes that affect part performance. Taking the bolt connection as an example, the effect of the bolt diameter and bolt space on the connection stiffness is analyzed, as shown in Figure 5. The results show that the bolt space has a more significant effect on the joint stiffness than the bolt diameter. Therefore, the connection constraint position sizes can be selected as the main optimization

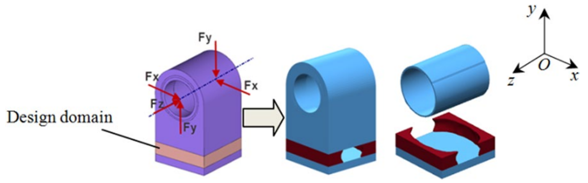
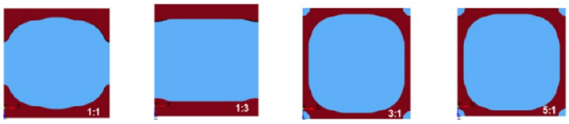


Figure 3 Physical optimization model of a machine tool spindle box and its bolt constraint domain



a F_x/F_y=1:1 **b** F_x/F_y=1:3 **c** F_x/F_y=3:1 **d** F_x/F_y=5:1

Figure 4 Relationship between the load value ratio and the bolt constraint domain

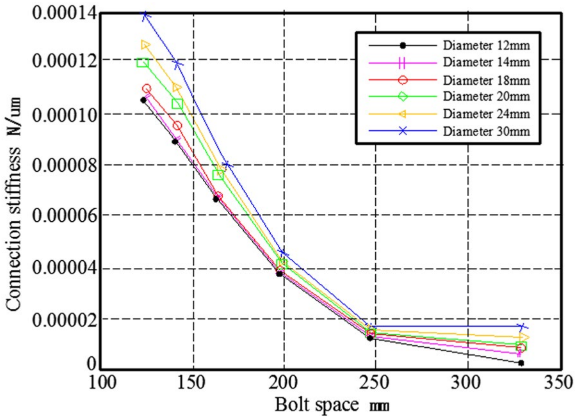
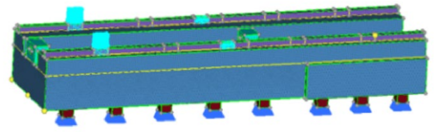
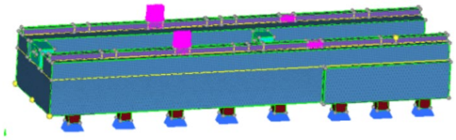


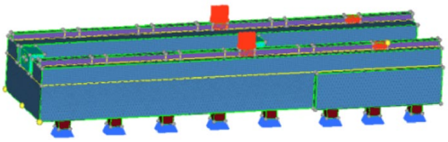
Figure 5 Influence of bolt space and bolt diameter on connection stiffness



a Left limit position

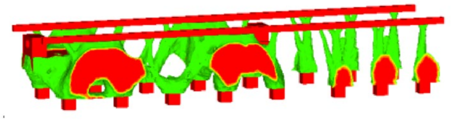


b Intermediate position



c Right limit position

Figure 6 Three working conditions of gantry-type machining center bed



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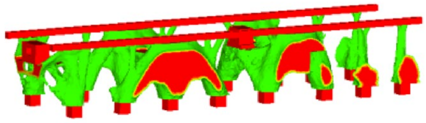
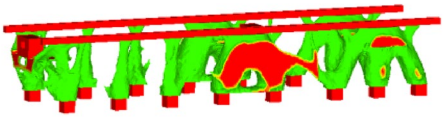


b Intermediate position



c Right limit position

Figure 7 Force routines under different working conditions of gantry-type machining center bed

variables in optimizing the sizes of bolt connection structure.

3.2 Force Routine-Performance-Main Structural Design of a Part

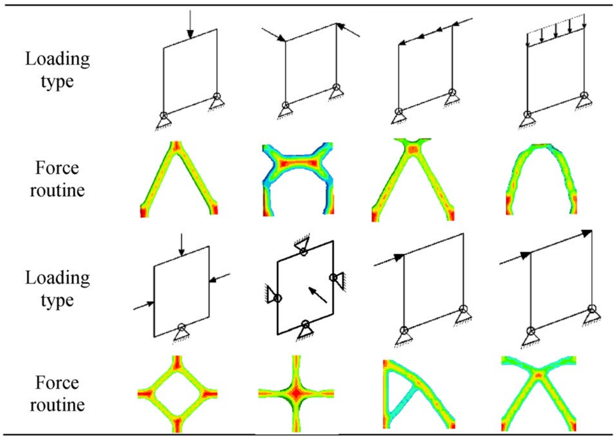
The main force routine of a part is mapped to its main structure. Based on the structural optimization model described in Section 2, the structural topology optimization considering multi-condition and multi-objective is carried out to obtain the main force transmission routine. In this paper, a gantry-type machining center bed was taken as example, where the loads are applied at the left and right extreme positions and intermediate position, respectively, as shown in Figure 6. The force routines of the main bed body under different conditions are obtained, as shown in Figure 7, for which it is found that different loads and constraints position directly affect the distribution of the force routine, thus affecting the part structure.

Due to common situations of material accumulation, and irregular and material fault in the structural topology optimization results, it is not possible to directly obtain the structure configuration. Therefore, the main structure needs to further refine the topology optimization results based on the configuration symmetry and configuration routine closure rules, to eventually realize the design from the conceptual design to the structure based on the force transmitting routine.

3.3 Force Routine-Performance-Sub-Structure Design of a Part

When the main structural sizes of a part is large, the whole and local performance of the part may not be good enough [29]. To this end, some sub-structures will often be attached to the main structure in the practice engineering problem [30]. Yan et al. [31], Huang et al. [32] and Zhou et al. [33] have researched on this field. In this paper, in order to simplify the structure of a part, the sub-structure is constructed of some basic structural configurations, which called as structural units, or their combination. The structural unit configurations are also mapped to the basic force routines under various loads, which may be obtained by using the structure topology optimization method and force-structure rule, as shown in Table 1. It is found that the force routines usually have “X”, “◇”, “+” and “V” configurations, namely, four kinds of structural units. The static performance of the various structural units is analyzed with the stiffness and mass ratio as the evaluation index, as shown in Table 2.

Table 1 Local force routine of units under various loads



By contrast, it is found that the performance of the structural units is different under the condition of different loads and same mass:

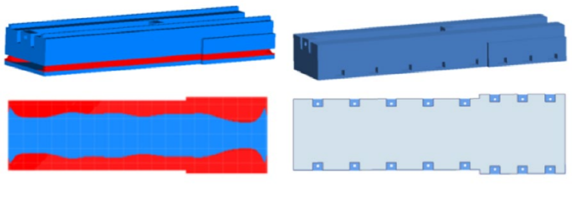
1. (1) The performance of V-shaped structure is the best, and the performance of X-shaped structure is the worst under pulling or pressure force.
2. (2) The +-shaped structure and V-shaped structure can bear greater vertical bending moment.
3. (3) The +-shaped structure shows the poor performance under the horizontal bending moment, while X-shaped structure can perform better under the same situation.
4. (4) The ◇-shaped structure has the better performance than others under the torque.

4 Light-Weight Design Example of a Part Performance-Structure

Based on the proposed co-operative optimization method for light-weight design of complex structure parts in this paper, a gantry machining center bed part as an example is designed on its connection constraints, the main and sub-structure configuration and the feature sizes. The design aims to achieve the light-weight design of the structure with optimal static and dynamic performance.

(1) Connection constraints design

The physical optimization model of bed bolt connection constraint is established. The constraint domain of the connection is calculated shown in Figure 8(a), and the connection structure is established according to the constraint domain, as shown in Figure 8(b).



a Constraint domain **b** Connection structure

Figure 8 Bed bolt constraint domain and connection structure

Table 2 Static performance of structural units

Unit type	Stiffness and mass ratio (kg mm)$^{-1}$			
	Pull force/pressure	Vertical bending moment	Horizontal bending moment	Torque
X	24.73	2.14	29.24	22.01
◇	27.15	2.15	29.18	22.43
+	37.26	2.50	21.45	16.90
V	30.84	2.45	25.41	21.38

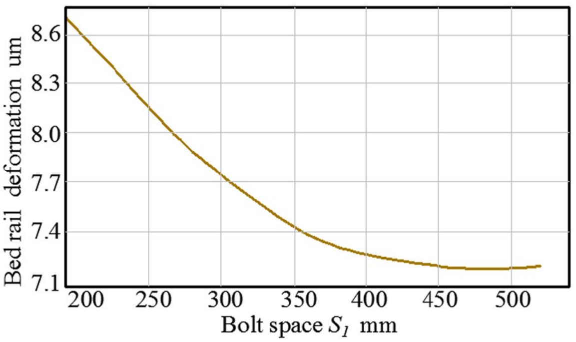


Figure 9 Relationship between bolt space and maximum deformation of bed rail

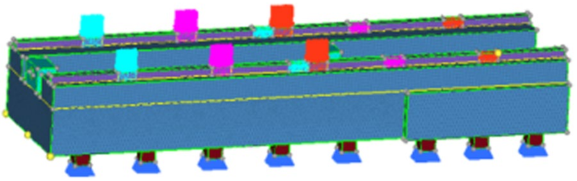
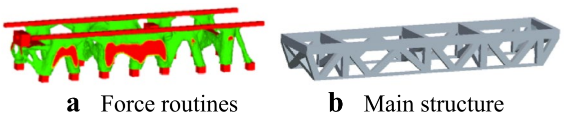
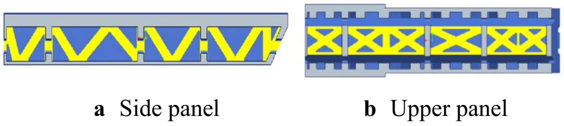


Figure 10 Physical model of the bed main body



a Force routines **b** Main structure

Figure 11 Force routines and bed main structure



a Side panel **b** Upper panel

Figure 12 The main structure and sub-structure of bed

Considering the maximum deformation of the bed rail as performance evaluation index of the bed, the functions between bolt space S_1 and the deformation of the bed rail are constructed firstly by using response surface method, as shown in Figure 9. And then for the purpose of minimizing the bed rail deformation, the bolt space is optimized, with the result 485 mm.

(2) Main structure design

According to the designed bolt joint structure in the previous section, the constraint position is determined, and the loads are applied by considering the two dangerous conditions and a typical working condition. The physical model of the bed main body is established, as depicted in Figure 10. As a result, the force routine and the main structure of the bed are obtained, as displayed in Figure 11(a) and Figure 11(b), respectively.

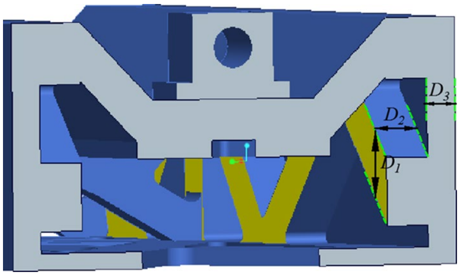


Figure 13 Optimized variables selection

(3) Sub-structure design

As the upper panel of the bed is mainly subject to bending moments, the X-shaped structural unit is added to the upper panel of the bed. The bed structure is established as shown in Figure 12. Figure 12(a) and (b) show the ribbed slab of side panel and the ribbed slab of the upper panel, respectively.

To optimize the width D_1, height D_2 of the ribbed slab and the panels' thickness D_3 of the bed structure as shown in Figure 13, the minimum bed mass and rail deformation are treated as the optimization goals. The function relationships constructed by response surface method between the optimization variables and the bed mass is shown in Figure 14. The functions between the optimization variables and the bed rail deformation are shown in Figure 15, and the corresponding results of the size optimization are shown in Table 3.

By using the finite element software, the optimized bed and the original bed provided by company are analyzed for a comparison. The deformation cloud of the optimized bed and the original bed are shown in Figure 16(a) and Figure 16(b), respectively. As seen from Table 4, the mass of optimized bed is lighter 8% than that of the original bed, but the rail deformation is reduced by 5%.

5 Conclusions

(1) A light-weight design method with structural topology and size co-operative optimization for the force-performance-structure of complex structural parts is proposed, which can effectively obtain structure configuration and main feature sizes under multi-condition. The proposed method can be carried out through topology and size optimization, applicable to connection constraint structure, main structure, and sub-structure.

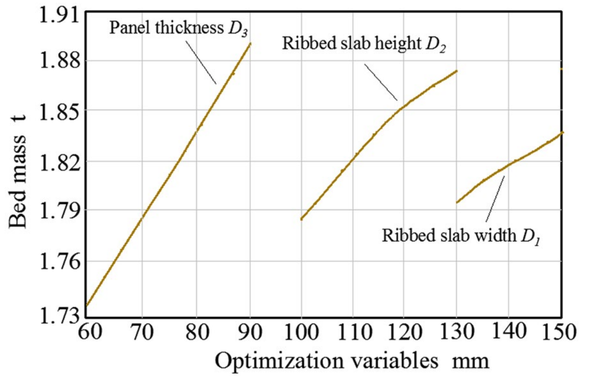


Figure 14 Relationship between the optimization variables and bed mass

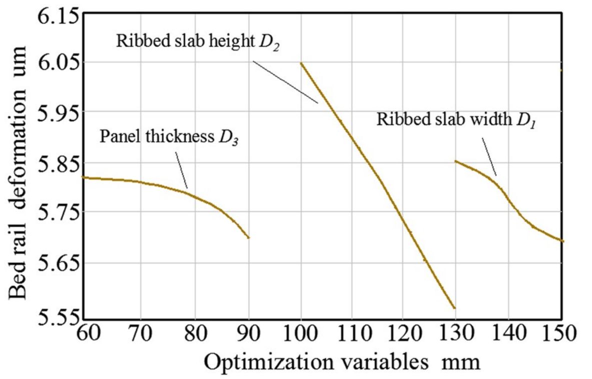
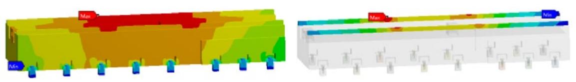


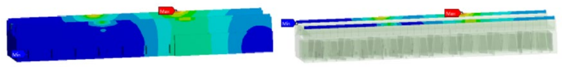
Figure 15 Relationship between the optimization variables and bed rail deformation

Table 3 Size optimization results

Type	Optimization result (mm)
D_1	140
D_2	100
D_3	65



a Deformation cloud of optimized bed



b Deformation cloud of original bed

Figure 16 Deformation clouds of optimized bed and original bed

Table 4 Comparison of bed performance

	Optimized bed	Original bed	Optimization percentage (%)
Mass (t)	17.1	18.5	8
Total deformation (μm)	8.0	8.1	1
Rail deformation (μm)	5.9	6.2	5

(2) The loads and constraints domain of a part (joint surface) directly affect the optimization results of structure, and the load ratio of different directions affects the optimization results of constraint domain distribution.

(3) The optimized bed is lighter 8% than original one, with the rail deformation reduced by 5%. Therefore, the light-weight design of the bed is realized with the enhanced performance.

Additional File

Additional file 1. Instructions of light-weight design method.

Authors' Contributions

Y-LM and J-RT was in charge of the whole trial; Y-LM and D-LW wrote the manuscript; Z-ZL assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Ethics Approval and Consent to Participate

Not applicable.

Funding

Supported by National Science and Technology Major Project (Grant No. 2015ZX04014021).

Publisher's Note

Received: 29 June 2017   Accepted: 16 April 2018

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