Knowledge-guided lightweight method for large complex component based on geometric-stress feature correlation response

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Abstract. Complex geometric features and stress features as well as their intricate relationships are the important factors causing the complexity of lightweight for large component. In order to better coordinate the stress distribution with lightweight goal, a knowledge-guided lightweight method based on geometric-stress feature correlation response is proposed. Multistage decomposition and three-steps feature express strategy is utilized to construct the geometric features relationship model firstly. By combining the influence significance for stress features with the association grade for geometric features, and reasoning under lightweight expectations, the geometric-stress correlation knowledge is extracted. Furthermore, a knowledge-guided lightweight algorithm integrated knowledge correlation response with intelligent searching is proposed. Finally, the lightweight of X-type caterpillar frame is taken as example to demonstrate the effectiveness of this method.

Key words. Large complex component; Geometric-stress feature correlation; Knowledge-guided lightweight; Knowledge correlation response; Integrated optimization

1. Introduction
Large complex components are the major bearing parts of engineering machinery. Comparing with other parts, it is more necessary to lighten the weight because of their large size and high energy consumption[1]. Many achievements have been realized by utilizing sensitivity analysis to guide lightweight or optimizing structural performances to tap lightweight potential[2][3]. Optimizing the stress distribution of component has become one of the most important ways for further lightening[4][5]. But due to the intricate relationship between geometry and stress distribution, the lightweight of large complex component is still difficult to be carried out. Considering the importance influence of geometric features on the stress distribution, it is necessary to seek a new breakthrough starting from the correlation between geometry features and stress features to improve the lightweight efficiency and effectiveness. Therefore, a new strategy of lightweight design guided by geometric-stress feature correlation knowledge is proposed in this paper.

2. Constructing geometric feature relationship model

Three-steps feature express (TSFE) process
Large complex component is usually welded by multiple plates, each of which has its own shape, size and location features. The changes of these features usually affect the stress distribution of component, but their influences are not the same. In order to guide lightweight design with the geometric-stress features correlation knowledge, the hierarchical relationships of geometric features for component as well as the association response of parameters should be identified firstly. Therefore, a geometric features relationship model based on TSFE method for large complex components is constructed and shown in figure 1. There are three sub-models obtained through this process.

![Figure 1. The process of constructing geometric feature relationship model](image)

### 2.1. Three sub-models in the geometric feature relationship model

**2.1.1. Component unit association (CUA) network sub-model.** According to the first step shown in figure 1, CUA network is constructed to express the layers and association relationships for complex structure. The top-down decomposition method is adopted to divide the component into multiple group branches, and then to decompose each branch layer by layer until the minimum component units according to the minimum relevance principle. By means of this decomposition, the layer connections among the units are expressed, and the association relationships of the units for the same layer are connected.

**2.1.2. Association response sub-model.** In the second step, the association relationships among component units are separated according to the CUA network model. Then, an association response model for the features is established. The association relationships, such as the association parameters, the location relationships and so on, are expressed by matrices and rules in this model. By running this model, the times of responding the association parameters and association relationships rules can be accumulated.

**2.1.3. Feature unit sub-model.** In the third step, the subdivision features of the final layer units in CUA network are expressed. Thus, the parameters in this layer for the units are determined and the association parameters responding from upper layers are accumulated. By this step, the relationships among the features and parameters are classified automatically. At the same time, the statistics of response can be realized to determine the association grade of structural parameters for the features.

### 3. The acquisition of geometric-stress feature correlation (GSFC) knowledge

Considering the intricate relationships between geometric features and stress features, it is meaningful to acquire GSFC knowledge for speeding up the lightweight of large complex component. The automatic process for acquiring GSFC knowledge is shown in figure 2, which contains two loops to show the relationships and process for knowledge acquisition. The outer-loop is constructed to handle the structural parameters information, the geometric features information and the stress features information,
which should be prepared for handling GSFC knowledge. On the basis, GSFC knowledge, which is acquired by combining the influence significance for the stress features with the importance for geometric features, is realized in the inner-loop.

In the one part of inner-loop, the correlation between structural parameters information and geometric features information is established by the geometric feature relationship model, which has been illustrated in section 2. In the other part of inner-loop, the influence grade matrix is acquired by the influence analysis module. The Monte Carlo simulation technique and the method based on Spearman rank correlation analysis are utilized[6]. The Spearman correlation coefficients are taken as the absolute influence of parameters for stress features and lightweight objects. According to these absolute influence knowledge as well as the reasoning under different coordinate expectations, the influence grade matrix can be obtained. By integrated reasoning the association grade matrix and the influence grade matrix, the GSFC knowledge is acquired.

![Figure 2. The automatic process for acquiring GSFC knowledge](image)

**4. Knowledge-guided lightweight strategy for large complex component**

The efficiency and effectiveness of the lightweight for large complex component are often unsatisfactory, because of containing complex features and too many parameters. It is necessary to seek a new lightweight strategy to solve this problem. In this section, a knowledge-guided lightweight strategy based on geometric-stress feature correlation response is proposed. By constructing a cycle of utilizing GSFC knowledge to guide lightweight optimization, the intelligent searching and knowledge adaptive responding are integrated. There are two important parts contained in the process of knowledge-guide lightweight optimization, which is shown in figure 3. The first part, which containing the selecting of lightweight branches and the responding of outer-loop information, is executed before the optimal searching, but the second part running in the cycle of searching is consisted of the responding of inner-loop knowledge and the population evolution. According to the different stages of optimization or the state of searching individuals during the process of lightweight, different optimization operators are generated by responding different GSFC knowledge.

![Figure 3. The process of knowledge-guide lightweight optimization](image)

In this process, different optimization tasks and geometric branches can be selected quickly according to the CUA network firstly, which provides a condition for realizing distributed lightweight optimization.
According to this CUA network, the outer-loop information, such as geometric features, the structural parameters, the stress features and the lightweight objects, can be responded.

Due to the different association and influence significance for geometric features and stress features, it is necessary to acquire GSFC knowledge adaptively to adjust different structural parameters. The inner-loop knowledge response and the population evolution should be formed as a cycle of optimal searching. By setting the significance threshold and correlation threshold, the corresponding GSFC knowledge matrix can be responded and reconstructed according to the coding of the optimal searching individuals. Furthermore, the lightweight-guide operators and the optimal operators can be updated to guide the population evolution.

5. Application

5.1. Getting the task of lightweight optimization

The lightweight optimization of X-type caterpillar frame is taken as an example in this paper. The geometric model and the CUA network of X-type caterpillar frame are shown in figure 4 and figure 5 respectively. The encoding and name of component units for this caterpillar frame are illustrated in table 1. According to the optimal process shown in figure 3, the lightweight task for optimizing the intermediate frame (No. N1-2) is carried out as example.

![Figure 4. Geometric model of caterpillar frame](image)

![Figure 5 CUA network of caterpillar frame](image)

| No. in figure 4 | Encoding in figure 5 | Name                   | No. in figure 4 | Encoding in figure 5 | Name                   |
|----------------|---------------------|------------------------|----------------|---------------------|------------------------|
| 1              | N1-1-1              | Carling                | 7              | N1-2-3              | Supporting plate       |
| 2              | N1-1-2              | Rib plate in carling   | 7              | N1-2-3-1            | Straight supporting plate |
| 3              | N1-1-3              | Baffle plate           | 7              | N1-2-3-2            | Bending supporting plate |
| 4              | N1-1-4              | Guide wheel support    | 8              | N1-2-4              | Supporting ring        |
| 5              | N1-2-1              | Lower cover plate      | 9              | N1-3                | Seat ring              |
| 6              | N1-2-2              | Upper cover plate      | 10             | N1-1-5              | Driving wheel support  |

5.2. The outer-loop information response of lightweight optimization

After getting the lightweight task for optimizing intermediate frame, the outer-loop information corresponding to this task is responded. The responded structural parameters are shown in figure 6. Among the structural parameters, there are 21 structural parameters are taken as optimization variables and illustrated in table 2. According to this out-loop information, the association response is realized by use of geometric features relationship model, and the response result for subdivision geometric features is shown in table 3. Furthermore, through the response of association rules, such as shape feature, size
feature, location feature and distribution feature, the parameter response accumulation is completed, and the association grade response matrix of parameters is obtained.

![Diagram of X-type caterpillar frame](image)

**Figure 6.** The responded structural parameters of of X-type caterpillar frame

**Table 2.** The optimization variables responded in this example

| No. | Symbol | Implication | No. | Symbol | Implication |
|-----|--------|-------------|-----|--------|-------------|
| 1   | T.     | Thickness of upper cover plate | 12  | G.     | Length of oblique line for U-type curve |
| 2   | T.     | Thickness of lower cover plate | 13  | G.     | Length of straight line for U-type curve |
| 3   | H.     | Distance from the top of upper cover plate to the bottom of track plate | 14  | G.     | Maximum longitudinal dimension for U-type curve |
| 4   | H.     | Distance from the bottom of the lower cover plate to the bottom of the track plate | 15  | G.     | Maximum width for U-type curve |
| 5   | X.     | Distance from the intersection of datum F4 and medial plate of carling to datum F3 | 16  | G.     | Lateral distance from the end of oblique line to the straight line for U-type curve |
| 6   | W.     | Distance between curved stiffener and plane stiffener | 17  | G.     | Length of oblique line for topological curve |
| 7   | W.     | Distance from the straight plate at the end of the curved stiffener to datum F1 | 18  | G.     | Longitudinal distance from the end of straight line to the end of oblique line for topological curve |
| 8   | L.     | Length of straight plate at end of curved stiffener | 19  | G.     | Longitudinal distance from the end of arc to the end of oblique line for the short edge of topological curve |
| 9   | T.     | Thickness of stiffener | 20  | G.     | Length of long edge of topological curve |
| 10  | D.     | Diameter of centre circle for cover plate | 21  | G.     | Maximum width for topological curve |

**Table 3.** The responded subdivision geometric features of the intermediate frame (No. N1-2)

| Component units | Feature class | Feature Name | Features encoding | Variables response | Relationship response |
|-----------------|---------------|--------------|-------------------|-------------------|----------------------|
| Lower cover plate | Basic | Rectangle steel | F1-1 | T., L., W., H. |
| N1-2-1 | Blanking | Cycle | F3-1-1 | D. | — |
| | | Irregular closed curve | F3-1-3 | G-G, | X, W |
| | | Irregular non-closed curve | F3-2-4 | G-G, | — |
| Upper cover plate | Basic | Rectangle steel | F1-1 | T., H. |
| N1-2-2 | Bending | Trapezoid | F2-2-3 | — | W, H. |
| | Blanking | Cycle | F3-1-1 | D. | — |
| | | Irregular closed curve | F3-1-3 | G-G, | X, W |
| | | Irregular non-closed curve | F3-2-4 | G-G, | — |
| Straight supporting plate N1-2-3-1 | Basic | Rectangle steel | F1-1 | T., W., X, T,T,H,H, W.D |
| Bending supporting plate N1-2-3-2 | Basic | Rectangle steel | F1-1-1 | T., W., X, T,T,H,H, W, G, G, G, G, D |
| | Bending | Arc | F2-2-1 | W, G, G, G, D |

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5.3. The inner-loop knowledge response of lightweight optimization

In order to optimize the intermediate frame, the maximum stresses in five different conditions, i.e., the equipment working in the angle of 0°, 30°, 45°, 60° and 90° from datum F1 to datum F3, are responded as stress features in this task. The absolute influences for stress features and lightweight object are shown in figure 7 and figure 8 respectively. According to the above absolute influence, the relative influence is obtained. After the rule reasoning under the guidance of lightweight expectation, the comprehensive influence significance of parameters for five stress features can be determined, as shown in figure 9. It means the influence significance of every parameter at its own grade. By integrating the association grade of structure parameters for geometric features, which is shown in figure 10, the GSFC knowledge can be acquired to guide the lightweight optimization.

5.4. The result of lightweight optimization

By using the knowledge-guided lightweight strategy proposed in this paper, the results of lightweight optimization are shown in table 4, where $M_{max}$ represents the maximum stress among the five feature stresses; $\Delta \bar{\sigma}$ represents the average difference between feature stress and allowable stress. Because the same material is used in every component unit, the volume is taken as the lightweight object. The cases from stage 1 to stage 4 are the different optimization stages guiding by different GSFC knowledge. When the searching fall into the state of evolutionary stagnation, the response threshold of GSFC can be
changed and the response knowledge can be updated accordingly. Therefore, the optimization parameters and operators can be adjusted timely according to the GSFC knowledge for further evolution.

In table 4, the volume in stage 4 are decreased by 28.97% comparing with initial case. In the case of satisfied the allowable stress, the frame is lightened effectively in this example. Comparing with the result of stage 1, both the volume and the $M_\text{max}$ are reduced in stage 2. It is indicated that the stress distribution become more reasonable in stage 2. In stage 3, the volume is further reduced than stage 2, which means that the evolutionary stagnation is overcome to tap lightweight potential under the guidance of GSFC knowledge. Comparing with the result of stage 3, the volume in stage 4 is reduced, but the $\Delta M$ is increased. It is shown that the decrease of volume does not mean every feature stress increase. Table 4 also shows that the volume can be reduced by adjusting the stress features under the guidance of GSFC knowledge. After four stages, the lightweight optimization has tended to converge.

| Case     | Volume (m³) | Feature stress (MPa) | $M_{\text{max}}$ (MPa) | $\Delta M$ (MPa) |
|----------|-------------|----------------------|-------------------------|-----------------|
| Initial  | 0.5133      | 119.57               | 109.81                  | 98.77           |
| Stage 1  | 0.4025      | 146.29               | 133.95                  | 121.80           |
| Stage 2  | 0.3863      | 145.31               | 135.85                  | 121.80           |
| Stage 3  | 0.3667      | 170.03               | 156.21                  | 141.94           |
| Stage 4  | 0.3646      | 171.52               | 158.66                  | 131.84           |

6. Conclusion

By taking the lightweight optimization of X-type caterpillar frame as example, the efficiency and effectiveness of proposed lightweight strategy is verified. The conclusions are shown as follows:

- The geometric feature relationship model can realize to respond GSFC knowledge according to the demand. By using the knowledge-guide lightweight optimization based on this model, the adaptive distributed lightweight decisions can be realized more easily.

- GSFC knowledge expresses the influence of structural parameters for the geometric features and the stress features comprehensively. Utilizing GSFC knowledge to guide optimization, the effectiveness of coordinating the conflict between structure performance and lightweight goal can be improved remarkably. It is also an effective strategy to overcome the evolutionary stagnation for further optimization.

7. Reference

[1] Vinola V M, William M B and John H. 2018 J. Vehicle fuel economy and vehicle miles travelled: an empirical investigation of Jevon’s Paradox (Energy Research & Social Science). vol 30 p19-27.

[2] Zhang D Q, Zhang T X, Zhang G S, Liu G C. 2011 Chinese J. Lightweight design for bus body frame based on sensitivity analysis (Journal of Mechanical Strength) vol 33 p 913-920.

[3] Zuo W J, Chen J S, Li Y W, Liu L. 2017 Chinese J. Size optimization on plate thickness of BIW with constraints of stiffness, strength and frequency (Automotive Engineering) vol 39(2) p145-149.

[4] Mehmet Yener. 2005. Design of a computer interface for automatic finite element analysis of an excavator boom (Turkey: Middle East Technical University) p 21-29.

[5] Na J X, He H J, Yan Y K, Chen L J. 2010 Chinese J. Lightweight design of vehicle body structure based on internal force optimization. Journal of Jilin University (Engineering and Technology Edition) vol.40 (6) p1492-1496.

[6] Xie W H. 2015 Chinese J. Variable screening based on Spearman correlation (Beijing University of technology). p13-29.

Acknowledgements

This project supported by the National Natural Science Foundation of China (No.51505085), the
Education Scientific Research Project for Middle-aged and Young Teacher of the Education Department of Fujian Province (No. JAT170374), and the Scientific Research Foundation Project of FuJian University of Technology (No. GY-Z14075). The authors would like to acknowledge the support of Digital Fujian Industrial Manufacturing IOT Lab and Fujian Key Laboratory of Automotive Electronics and Electric Drive (Fujian University of technology).