Optimization Method of Segmented Grain Structure Based on Shortest Distance Proxy Model

Jiuling Zhao
Department of Power Engineering, Rocket Force University of Engineering, Xi’an Shaanxi 710025, China
Email: zhaojiuling111@163.com

Abstract. The structural integrity of the grain is very important for the grain with complex geometry. Large section column structure has its particularity, differs from that of a single column, its length to diameter ratio is large and absolute meat the increase of the thickness, particles of geometric shape and size of the key factors to determine the gas production rate and its change rule of the engine, at the same time, the engine thrust and pressure change with time, particle size determines the volume and weight of the combustion chamber, Therefore, the particle design of solid rocket motor determines the quality design index of the engine to a large extent. In order to improve the efficiency of model optimization, an agent model is established in this paper. The prediction accuracy of the model depends on the distance between prediction points and sample points. The shortest distance hierarchical clustering algorithm is used to improve the prediction accuracy. Through the research, the comprehensive effect of the key factors affecting the structural integrity of the propellant and the law of the influence on the structure and safety margin of the propellant are obtained. The research method and law can provide support for the large solid motor grain design, and provide theoretical reference for the solid rocket motor grain structure multi-parameter optimization design.

Keywords. Segmented grain structure; shortest distance proxy model; optimization method.

1. Introduction
The geometric shape and size of solid motor grain determine the gas generation rate and its variation law of the engine, which also determines the change of thrust and pressure of the engine with time. At the same time, the grain volume determines the volume and weight of the combustion chamber. Therefore, the grain design of solid rocket motor determines the internal ballistic performance and quality index of the motor to a great extent. Large-scale segmented grain structure has its particularity, which is different from monolithic grain in that the ratio of length to diameter is large and the absolute meat thickness increases [1].

In this paper, aiming at the main factors affecting the structural integrity of large-scale segmented engine grain, the influence laws and reasons of important factors in the design of grain structure are explored, and the different laws of key design parameters of large-scale segmented grain affecting the structural strength of grain are explored. The influence law of the comprehensive effect of key factors on grain structure integrity on grain structure and safety margin is obtained, and the best matching strategy is obtained, which provides support for large solid motor to realize grain design and theoretical reference for multi-parameter optimization in solid rocket motor grain structure design, so
as to obtain guiding conclusions for design, thus avoiding accidents caused by structural design defects and other possible reasons.

2. Optimization Design of Meso Model based on Hybrid Genetic Algorithm

Kriging model is a kind of unbiased estimation model with minimum estimation variance, which has the characteristics of local estimation. Moreover, the continuity and derivability of the correlation function are also good, and the ideal fitting effect can often be obtained when solving the problems with high degree of nonlinearity [2]. It is concluded that the prediction accuracy mainly depends on the distance between the prediction point and the sample point. Generally speaking, the closer the distance between the prediction point and the sample point, the higher the prediction accuracy, and vice versa [3-5]. The Algorithm flow is shown in figure 1.

In this paper, the shortest distance hierarchical clustering algorithm is used to improve the prediction accuracy. The process is to count all the sample points of the study as one class, cluster the closest one first, and then combine this class with the closest one in other classes, thus continuing to merge until all objects are integrated into one class or meet a threshold condition [6, 7].

In the following, \( d_{ij} \) is the distance between samples \( x_i \) and \( x_j \). \( D_{ij} \) is expressed by the distance between \( G_i \) and \( G_j \). Define the distance between class and as the distance between the two nearest samples, namely,

\[
D_{ij} = \min_{x_i \in G_i, x_j \in G_j} d_{ij}
\]

If the class \( G_p \) and \( G_q \) are combined into a new class \( G_r \), then the distance between any class \( G_k \) and \( G_r \) is:

\[
D_{kr} = \min_{x_i \in G_k, x_j \in G_r} \min_{x_i \in G_p, x_j \in G_q} \min_{x_i \in G_p, x_j \in G_q} = \min\{D_{kp}, D_{kq}\}
\]

The steps of shortest distance clustering are as follows [8]:

1. Define the distance between samples, calculate the two distances of samples, and get a distance from the matrix of \( D_{(0)} \), and each sample is a kind of self-being, which is obvious at this moment \( D_{ij} = d_{ij} \).

2. Find out the minimum element \( D_{(0)} \), then combine \( G_p \) and \( G_q \) into a new class, \( G_r = \{G_p, G_q\} \)

3. A formula for calculating the distance between the new class and other classes is given:

\[
D_{kr} = \min\{D_{kp}, D_{kq}\}
\]

Combine the rows \( P \) and \( Q \) of \( D_{(0)} \) into a new row and column, and record the obtained matrix corresponding to \( D_{(1)} \).

4. Repeat the above-mentioned pair (2), (3) get it in two steps; And so on, until all the elements are grouped together.

If there is no limit to one of the smallest elements of \( D_{(k)} \), the classes corresponding to these smallest elements can be merged at the same time.

The algorithm flow of model optimization based on the above ideas is shown in the following figure.
3. Application of Optimization Model in Structural Design of Segmented Grain

In the process of grain structure optimization, it is necessary to establish the expression of objective and constraint function. Because of the complex geometric structure of solid rocket motor, it is difficult to establish the expression of objective and constraint function. In this paper, eight proxy models are established to replace the time-consuming finite element calculation process, which improves the optimization efficiency of solid rocket motor. Based on the idea of distributed optimization, the best optimization model is finally obtained [9]. The general idea of optimization is shown in figure 2.

The optimization process is divided into three stages [10]:

1. Building a low-precision proxy model to obtain the best depth and subsection ratio

Based on the proposed problems, the primary agent model is constructed, and the value range of human detachment depth and subsection ratio in the reserved subspace is determined through the process of space reduction. The optimal solution is obtained by searching in the reduced space: the debonding depth is 1.1D, and the subsection ratio is 4.5:5.5.

2. Under the optimal debonding depth and subsection ratio, based on the primary proxy model, the relationship between M number and maximum strain is obtained. The model was built under the structure size of 1.1D debonding depth and 4.5: 5.5 subsection ratio of the front and back sections of the grain, the structures with M numbers of 2, 2.2, 2.4, 2.6 and 2.8 were analyzed under four loads, and the relevant laws were obtained.

It can be seen from figure 3a that with the increase of M number under curing cooling load, the maximum strain of drug column under curing cooling load gradually increases, and the growth rate gradually increases.

It can be seen from figure 3b that with the increase of M number under vertical storage load, the maximum Von Mises strain of the cartridge under vertical storage load gradually increases and basically shows linear growth.
Figure 2. Influence of debonding depth on structural integrity under different inner diameter sizes.

(a) Solidification cooling load
(b) Vertical storage load
(c) Ejection overload
(d) Working internal pressure load

Figure 3. Influence of four loads of m number on grain structure.
It can be seen from figure 3c that the maximum Von Mises stress of grain gradually increases with the increase of m number under ejection overload load, and the growth rate gradually increases. It can be seen from figure 3d that the maximum Von Mises stress of grain gradually increases with the increase of m number under the working internal pressure load, and the growth rate gradually increases.

(3) A high-precision agent model is constructed, and the model structure under the most suitable safety factor and the maximum loading fraction is determined. From table 1, we can see that relative errors of four loads between agent model and calculated result is less than 2%.

| Load                     | Relative error (%) |
|--------------------------|--------------------|
| Curing and cooling       | 1.4                |
| Vertical storage         | 1.7                |
| Overload                 | 1.5                |
| Working Internal Pressure| 2.0                |

In the range of allowable strain, based on the structural strength, the best M number is 2.68 under the limited safety factor, and the loading fraction at this time is 85.56%.

4. Conclusion

Aiming at the main factors affecting the structural integrity of large-section columns, the influence of the important factors and key design parameters in the design of charging structure on the particle size effect of different structural strengths is discussed. According to the influence of each key element combination on the structural integrity of the propellant column, the influence law of safety margin and the optimal matching strategy, in the process of structural optimization, an agent model was established to replace the time-consuming finite element calculation process, which improved the optimization efficiency of solid rocket motor. Based on the idea of step-by-step optimization, the optimal optimization model was finally obtained. The method presented in this paper can provide support for the charging design of large solid engines to avoid accidents caused by structural design defects and other possible reasons.

References:

[1] Ruan C Z, Zhang Y Z, Chen R X, et al. 2004 Solid Rocket Motor Design and Research (Part I) (Beijing: Astronautics Press).
[2] Namazifard A, Hjelmstad K and Sofronis P 2005 Simulations of propellant slumping in the Titan IV SRMU using constitutive models with damage evolution AIAA 2005-3994.
[3] Han Z 2016 Kriging surrogate model and its application to design optimization: A review of recent progress Acta Aeronauticaet Astronautica Sinica 37 (11) 3197-3225.
[4] Zhang J and Ma Y 2020 A multi-points infill sampling criterion and parallel surrogate-based optimization algorithm based on Kriging model System Engineering Theory and Practice 40 (1) 251-261.
[5] Nie X-Y, Liu Z-Y, et al. 2017 Aircraft structure stiffness and aerodynamics optimization design based on kriging surrogate model Physics of Gases 2 (2) 8-16.
[6] Yu J X, Liu L M, et al. 2003 On nonlinear stability analysis of ship structure Journal of Ship Mechanics 7 (6) 75-83.
[7] Gao E Z, Li H W, et al. 2009 Influences of material parameters on deep drawing of thin-walled hemispheric surface part Transactions of Nonferrous Metals Society of China 2009 (19) 433-437.
[8] Bellini P X and Chulya A 1987 An improved automatic incremental algorithm for the efficient solution of nonlinear finite element equations Computers & Structures 26 (1) 99-110.
[9] Finne S, Futsaether C, et al. Three-dimensional analysis of solid propellant grain using a nonlinear viscoelastic model AIAA 1990-2090.

[10] Meng S, Tang G, et al. 2004 Method for obtaining optimum depth of artificial debonding layer of solid rocket motor Guangxi Science 11 (2) 106-108.