Structural design flow of typical aircraft components based on topology optimization

Zhijie Feng¹, Jianbin Du², Haixi Zhang³ and Kai Wu²,³

¹ AVIC Aerospace Life-support Industries.Ltd, 441000, Xiangfan, China; ² School of Aerospace Engineering, Tsinghua University, 100084, Beijing, China
³ Email: wuk17@mails.tsinghua.edu.cn

Abstract. In the field of structural topology optimization, an important but often neglected problem in previous studies is how to translate the optimal conceptual design obtained by topology optimization to engineering CAD model which can meet requirements of reliability and manufacturability efficiently. This paper carried out exploratory research on full stage design of typical aircraft components. A set of integrated schemes are proposed as a complete design flow from the conceptual design to engineering geometry scheme, including multi-objective dynamic topology optimization, transformation from the optimal topological conceptual design to engineering geometry model, CAE analysis and manufacturing by 3D printing. The method above has strong portability and broad application prospects, which can provide references and technical routes.

1. Introduction

During the voyage, adverse vibrations may occur on the flight vehicles’ key components such as cabin, rudder and wing, which do great harm to the working condition and life-span of the whole structure. The main design method now used is to perform vibration suppression by artificially adjusting the counterweights and dimension parameters. Most of the time this kind of empirical design is inefficient and difficult to consider the integration of the whole system. Therefore, it is worthwhile to do structural optimization such as structural topology optimization to eliminate the risk of adverse vibration by keeping the structure’s fundamental frequency away from the interval of the excitation frequency, especially at early conceptual design stage.

Topology optimization is an efficient method with tremendous freedom for structural design. Compared to size optimization and shape optimization, topology optimization can derive novel conceptual designs which are not subjected to any inherent form. Undesirable vibration and noise emission levels can be mitigated through dynamic topology optimization. Du discussed topology optimization for maximum values of simple and multiple eigenfrequencies and frequency gaps [1]. Olhoff and Niu design band-gap structures by shape optimization of transversely vibrating Bernoulli–Euler beams [2]. On the other hand, a lot of studies have been made about topology optimization for practical application. Xiao designed an electric bicycle main frame considering structural dynamic performances based on topology optimization [3]. Beghini proposed a tailored structural topology optimization framework to achieve balance between the architectural and structural engineering communities [4]. Takanori researched structural topology optimization for gear box of automatic transmission of vehicles with contact constraints [5].
However, an important problem which has not been solved well in the field of structural topology optimization is how to translate the optimal conceptual design obtained by topology optimization to engineering CAD model efficiently. Another interesting and relevant problem is how to reduce the change caused by translation from topological conceptual design to engineering model [6-8].

In this paper, we put forward a systematic design flow to implement structural design from topological optimization design to engineering geometry scheme, including multi-objective dynamic topology optimization, transformation from the optimal topological conceptual design to engineering geometry model, CAE analysis and 3D printing. The method above has strong portability and broad application prospects, which can provide references and technical routes.

This paper is organized as follows: In Section 2, we discuss the basic formulation of multi-objective topology optimization based on density-based method. In Section 3, a systematic design flow is presented as reference. Section 4 presents the structural design flow of an aircraft rudder as numerical example. Some discussions are made in Section 5.

2. Basic theory of topology optimization
We here use density-based topology optimization method, which uses element volume density as design variable. The topology optimization problem can be rebuilt mathematically as 0-1 integer programming problem in this way. However, 0-1 integer programming problem is ill-posed, which manifests itself by mesh-dependence and lack of convergence. Methods such as SIMP (Solid Isotropic Microstructure/Material with Penalty) are introduced as regularization to make it well-posed. SIMP defines artificial density which can range from 0 to 1 continuously on each finite element, element with intermediate artificial density can be deemed as composite material. The equivalent material properties are obtained from a predefined artificial interpolation model. Further introduce filter and projection technique to eliminate checkerboard and make the artificial density converge to 0-1 [9-11].

The mathematic equations used in our optimization model for the rudder (Section 4) can be written as follows, by using weighted dimensionless method, the multi-objective optimization problem is transferred into an equivalent single objective optimization problem:

\[
\begin{align*}
\min_{\rho_e} & \left\{ f = w_1 \overline{f_1} + w_2 \overline{f_2} + w_3 \overline{f_3} \right\} \\
\text{s.t.} & \quad f_1 = C = P^T U \\
& \quad f_2 = \frac{1}{\omega_j^2} \\
& \quad f_3 = \frac{1}{\omega_j^2 - \omega_k^2} \\
& \quad KU = P \\
& \quad K \varphi_j = \omega_j^2 M \varphi_j, \quad j = 1, \ldots, J \\
& \quad \varphi_j^T M \varphi_j = \delta_{jk}, \quad i \geq k, \quad k, j = 1, \ldots, J \\
& \quad \sum_{e=1}^{N_e} \rho_e V_e \leq V^* \\
& \quad 0 < \rho_e \leq 1, \quad e = 1, \ldots, N_e
\end{align*}
\]

Where K is the total stiffness matrix, M is the structural mass matrix, U is the array of nodal displacement, P is the nodal force vector. \( \varphi_j \) is the j-th structural modal shape, \( \omega_j \) is the j-th structural modal eigenfrequency. \( \rho_e \) is the relative volume density of each element, \( V_e \) is the volume of each element, \( V^* \) is the upper limit of structural overall volume. \( N_e \) is the number of finite elements.

Sensitivity analysis, density filter technique, volume relaxation technique and additional penalization technique are also applied here [12-14].
3. Design flow chart and technical route

The design flow chart is shown as Figure 1, we propose this systematic design flow to implement structural design from topological optimization design to engineering geometry scheme, including initial structure scheme, initial finite element model, multi-objective topology optimization, parameterized model of the conceptual design, analysis and verification, 3D printing or traditional manufacturing.

Firstly, we establish a finite element model based on the initial practical model as the design domain. Since the final optimization results are related to those parameters used in iterations, we use control variable method to investigate how volume fraction and the distribution of objectives’ weighting coefficients can affect the static and dynamic performances of the final optimal configuration. A set of complete iterations should be done for each parameters combination, so a rough-meshed finite element model is recommended because of calculation efficiency.

After that, preferable optional conceptual designs are chosen from Pareto solution set obtained from above multi-objective topology optimization according to mathematical criteria and engineering experience. Then we establish the parameterized model of the most suitable conceptual design by using ANSYS APDL with reference to the optimal topological configuration and validate the corresponding finite element model numerically. The size parameters of the parameterized model are modified slightly so that its indices of weight reduction and the static and dynamic properties are close to those of the original optimal topological result. Finally, the parameterized and numerically validated geometry model is imported into SolidWorks in preparation for being transferred into the format which is suitable for 3D printers or other manufacturing methods.

**Figure 1.** Flow Chart.
4. Numerical examples
Rudder is a typical control mechanism on a missile. Here we manage to propose a lighter structure which can reduce the maximum deformation, as well as meeting the requirements for mechanical properties.

4.1. Model Establishment and Definition
A practical model of a kind of rudder now used in reality can be seen in Figure 2. We use it as the initial design domain (The topological configuration for the first iteration step is the model with uniform artificial density). The upper and lower skin, the shaft are defined as passive domains which do not participate in design, the middle skeleton is the main design area. Pneumatic pressure, deadweight, overload acceleration are applied on the rudder and it is completely fixed at the shaft. The static and dynamic performances of the initial practical model are used as criteria: The structural mass should be less than 3.05 kg, the fundamental frequency should exceed 252 Hz, the gap between the first and the second eigenfrequency should be more than 19 Hz, and the maximum structural displacement should be limited under 18 mm.

Figure 2. Rudder’s practical model.

4.2. Pareto Solution Set of Multi-objective Topology Optimization
As can be seen from equation 1, different optimal topology configuration will be obtained by adjusting the weight coefficients of sub-objectives while keeping other optimization parameters constant (e.g. the volume fraction is set to 0.3, which means there is no weight reduction). Volume fraction refers to the percent of material that will be retained during the optimization iterations. We here take the following three sub-objectives into consideration:

1) Minimize the structure’s static compliance, weight coefficient $w_1$
2) Maximum the fundamental frequency, weight coefficient $w_2$
3) Maximum the gap between the 1st and 2nd eigenfrequencies, weight coefficient $w_3$

If $w_1$ and $w_2$ are known, $w_3$ can be uniquely determined by $w_1 + w_2 + w_3 = 1$. Changing $w_1$ and $w_2$ to investigate how the weight coefficients affect the rudder’s static and dynamic performances. Figure 3 shows the scatter diagram of the Pareto solution set.

In order to improve the efficiency, we use rough meshed finite element model in this section. After getting all the optimal topology configuration of those different weight coefficients, we pick out those weight coefficients combinations (marked red in Figure 3, listed in Table 1 whose final topological configuration has a better overall dynamic performances. Considering the mechanic performances and the stability of the iterative process comprehensively, (0.1, 0.8, 0.1) and (0.3, 0.4, 0.3) are chosen as the most satisfied weight coefficient combinations.

4.3. Weight Reduction
Then we do light weight analysis based on the above two sets of weight coefficients. For each set, changing the volume fraction from 0.5% to 20% in steps of 0.5%, then do topology optimization on
each volume fraction. As can be seen in Figure 4, also make a plot to reveal how the final topological configuration’s mechanical performances change bias to volume fraction (structural mass).

Ensuring that the final topological configuration’s mechanical properties can satisfy those requirements, the structural weight should be reduced as much as possible. Finally, we choose the scheme whose volume fraction is 11.5% under weight coefficients (0.3, 0.4, 0.3) for the next steps.

![Figure 3](image)

(a) Structural maximum deformation  (b) Fundamental frequency  (c) Gap between 1\textsuperscript{st} and 2\textsuperscript{nd} frequencies

Figure 3. Scatter diagram of the Pareto solution set.

| $w_1$ | $w_2$ | $w_3$ | $\text{Freq}_1$ (Hz) | $\text{Freq}_2$ (Hz) | $\text{FreqGap}$ (Hz) | MaxDisp (mm) |
|-------|-------|-------|-----------------------|-----------------------|-----------------------|--------------|
| 0.01  | 0.89  | 0.10  | 271.83                | 300.40                | 28.57                 | 13.38        |
| 0.10  | 0.80  | 0.10  | 271.62                | 299.95                | 28.33                 | 13.61        |
| 0.20  | 0.70  | 0.10  | 270.78                | 298.79                | 28.02                 | 13.80        |
| 0.30  | 0.60  | 0.10  | 270.39                | 298.78                | 28.39                 | 13.84        |
| 0.40  | 0.50  | 0.10  | 270.17                | 298.79                | 28.62                 | 13.90        |
| 0.01  | 0.79  | 0.20  | 271.06                | 301.82                | 30.76                 | 13.27        |
| 0.10  | 0.70  | 0.20  | 270.98                | 301.27                | 30.28                 | 13.21        |
| 0.20  | 0.60  | 0.20  | 270.67                | 300.25                | 29.58                 | 13.37        |
| 0.30  | 0.50  | 0.20  | 271.38                | 300.70                | 29.32                 | 13.41        |
| 0.40  | 0.40  | 0.20  | 270.60                | 299.73                | 29.13                 | 13.56        |
| 0.50  | 0.30  | 0.20  | 270.25                | 299.10                | 28.85                 | 13.81        |
| 0.10  | 0.60  | 0.30  | 270.54                | 302.58                | 32.03                 | 13.43        |
| 0.20  | 0.50  | 0.30  | 270.17                | 302.04                | 31.87                 | 13.35        |
| 0.30  | 0.40  | 0.30  | 270.15                | 301.79                | 31.64                 | 13.14        |

\(^{a,b}\) $1^{\text{st}}$ and $2^{\text{nd}}$ eigenfrequency of the optimal topological configuration.
4.4. Validation of the Optimum Topological Design Based on Fine Meshed Model
Then we perform topology optimization based on fine meshed finite element model in order to make a comparison with results obtained from rough meshed model. As can be seen from Table 2, the optimal topological configuration’s mechanic performances are just slightly changed after the grid encryption.

Table 2. Comparisons of Mechanical properties between different designs.

| Optimum designs     | VoluFrac | Freq1(Hz) | FreqGap( Hz) | MaxDisp (mm) | Mass optimal(kg) | Mass reduce(kg) |
|--------------------|---------|----------|-------------|-------------|-----------------|-----------------|
| Rough meshed       | 0.115   | 249.11   | 30.23       | 16.13       | 2.70            | 0.35            |
| Fine meshed        | 0.115   | 255.30   | 26.67       | 15.76       | 2.66            | 0.39            |
| Parameterized model| --      | 245.69   | 35.30       | 15.63       | 2.68            | 0.37            |
| Practical model    | --      | 252.00   | 19.00       | 18.00       | 3.05            | 0               |

4.5. Validation of the Optimum Topological Design Based on Fine Meshed Model
Establish a parameterized model of the optimal design by using ANSYS APDL with reference to the final topological configuration and perform an adjustment design based on manufacturing criteria and engineering experiences. The size parameters of the parameterized model are modified slightly so that its indices of weight reduction and the static and dynamic properties are close to those of the original optimal topological result. The model is also chamfered to avoid stress concentration. After that, we check the displacement, eigenfrequencies, stresses and strains of the final parameterized model in ANSYS.

The final parameterized model’s mechanical properties are also shown in Table 2. Though its fundamental eigenfrequency is a little bit lower than the practical model’s, the gap between the 1st and 2nd eigenfrequencies as well as the structure’s maximum deformation have improved a lot, and the structure’s weight is reduced by 0.37 kg. At last, the parameterized model is imported into SolidWorks in preparation for being transferred into a STL format that is suitable for 3D printers.

The structural models corresponding to each steps in this design flow can be seen in Figure 5.

5. Conclusions
In this paper, we propose a set of integrated schemes as a complete design flow of topological design for complex engineering structure, which has strong portability and broad application prospects. Beside, the rough meshed finite element model is used when doing analysis on distribution of multi-objective weight coefficients and weight reduction. After picking the best set of volume fraction
and weighting coefficients, the fine meshed finite element model is adopted for validation and parameterization. The static and dynamic performances of the two optimal topology structures remain close to each other. It reveals that the optimization result obtained from rough meshed finite element model is also trustworthy and more efficient.

In the end, we get a subversive configuration of the rudder which does not rely on any previous design. Compared to the practical model used now in reality, the new structure is much lighter while its mechanical properties can still meet the requirements.

![Finite element model](image1)
![Optimal topology configuration](image2)
![Engineering parameterized model](image3)
![Analysis and Verification](image4)
![Transformation into STL](image5)
![3D printing Model](image6)

**Figure 5. Structural Models.**

**Acknowledgement**

The research is supported by NSFC (11772170), the Key Laboratory of Spacecraft Design Optimization and Dynamic Simulation Technologies (Beihang University), Ministry of Education, China under Grant No. 2019KF001, and the Project on Electric Driver Seat Technology for Large Passenger Aircraft (MJ-2018-S-44), which is gratefully acknowledged by the authors.

**References**

[1] Jianbin Du, Olhoff N 2007 Topological design of freely vibrating continuum structures for maximum values of simple and multiple eigenfrequencies and frequency gaps *Struct Multidisc Optim* 34 91-110

[2] Olhoff N, Bin Liu, Cheng GD 2013 Optimum design of band-gap beam structures *International Journal of Solids and Structures* 49 3158–3169

[3] Denghong Xiao, etc. 2012 Application of topology optimization to design an electric bicycle main frame *Struct Multidisc Optim* 46 913-929

[4] LL. Beghini, etc. 2014 Connecting architecture and engineering through structural topology optimization *Engineering Structures* 59 716-726

[5] Takanori Ide, etc. 2016 Structural optimization methods of nonlinear static analysis with contact and its application to design lightweight gear box of automatic transmission of vehicles *Struct Multidisc Optim* DOI 10.1007/s00158-015-1369-y

[6] Eschenauer HA, Olhoff N 2001 Topology Optimization of Continuum Structures: A Review *Applied Mechanics Review* 54(4) 331-389

[7] Guo X, Cheng GD 2010 Recent Development in Structural Design and Optimization *Acta Mechanica Sinica* 26(6) 807–823

[8] Deaton JD, Grandhi RV 2014 *A Survey of Structural and Multidisciplinary Continuum*
Topology Optimization: Post 2000 Springer-Verlag New York

[9] Jianbin Du 2015 *Structural Optimization and its Application in Vibrations and Acoustic Designs* Tsinghua University Press

[10] Haug E J, Choi K K, Komkov V 1986 Design Sensitivity Analysis of Structural Systems *Vol.177 of Mathematics in Science and Engineering*, Orlando: Academic Press

[11] Bendsøe M P 1989 Optimal Shape Design as a Material Distribution Problem *Structural Optimization* 1 193-203

[12] Rozvany G I N, Zhou M, Birker T 1992 Generalized Shape Optimization without Homogenization *Structural Optimization* 4(3-4) 250-252

[13] Bendsøe M P, Sigmund O 1999 Material Interpolation Schemes in Topology Optimization *Archive of Applied Mechanics* 69 635-654

[14] Sigmund O, Peterson J 1998 Numerical Instabilities in Topology Optimization: A Survey On Procedures Dealing with Checkerboards, Mesh-Dependencies and Local Minima *Structural Optimization* 16(1) 68-75