# Optimization of Complex Structure Based on Human-Computer Interaction Method

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**Abstract.** To solve the problem of structural optimization of complex structure under dynamic response constraints, a human-computer interaction method was proposed combined with advantages of human and computer in structural optimization, and being used in structural optimization of an aerospace assembly to verify its practicability and effectiveness. The method was mainly based on two steps: topology optimization by human-computer interaction and size optimization by computer. The aerospace assembly after structural optimization based on the method could satisfy the dynamic environment requirement and the results showed that first integral vibration frequency raised 41.1 % and magnification of acceleration dropped 25.2 % while the mass remained essentially unchanged. Also the experimental results compared with the simulation results showed that the relative error was less than 5 %, which proved the effectiveness of the simulation design. The human-computer interaction method might provide a reference for similar products not limited to aerospace field.

**Keywords:** Structure optimization · Human-computer interaction method · Aerospace assembly · Dynamic response constraints · Topology optimization by human-computer interaction · Size optimization by computer

## 1 Introduction

Spacecraft will experience complex mechanics environment in the process of launching, and vibration is one of most important factors to be considered in the development phase of space products. Also spacecraft is strict to quality characteristics because the cost can decrease 10000 dollars as the weight reduces 1 kg [1], and one of the most important factors that limit human to explore space is the weight. For these many reasons, people often choose to use structural optimization technology to find the minimum mass and cost under the given constraints [2].

Although people wish the structure can be the most suitable in the initial process of the development, the space products either may not satisfy the constraints or have large useless material allowance constantly at the beginning. There are two methods to solve the problem; one is traditional means by manual work that the designer can modify the structure by experience again and again. The advantage of this way is that the direction is clear so the designer can adjust the project at any time to find the better structure. Also in the design process, the designer can consider the manufacturing and installing constraints adequately. However, the disadvantage also exists that this way may just

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find a good scheme but not the best structure. On the contrary, structural optimization by computer can find the best solutions through numerical iteration, but the disadvantage is that computing amount is too large for complex problem such as topology optimization for complex structure under dynamic response constraints.

Researching structural optimization problem under dynamic environment is of great importance [3], but the issue is difficult to solve because of complexity of the sensitivity analysis [4] and hugeness of the computing amount, and remain some theoretical problems to research [5], especially for the topology optimization [6, 7]. For this reason, people often translate the dynamic problems to the static problems according to the given principles. But the static method cannot reflect the influence of the free vibration item and damping, hence the situation often happens that static equivalent condition can satisfy the requirement but the dynamic condition cannot. Considering all above factors, a human-computer interaction method is proposed to solve the optimization of complex structure under dynamic response constraints.

## 2 The Human-Computer Interaction Method

There are frequency constraints, dynamic response constraints including dynamic response displacement constraints, dynamic response acceleration constraints, and dynamic response stress constraints and so on in dynamic environment structural optimization [8, 9]. And structural optimization has three levels, which are size optimization, shape optimization, and topology optimization. Topology optimization is often used in the concept phase in the optimization progress, and can make significant impact for the improvement of mechanical performance [10]. In consideration of the complexity of topology optimization by computer, we choose to take advantage of the manual work to modify the topology structure, in other words, this stage is topology optimization by human-computer interaction style. Then we can use size optimization to find the best size of the structure under the dynamic response constraints by guidelines method or mathematical programming approach methods.

Human-computer interaction method makes use of advantages of human and computer in structural optimization adequately [11, 12]. Its process concludes the following stages. Firstly, the finite element model can be created by finite element software and the model can be updated by some ways such as modal test to achieve a relatively accurate model. And modal analysis and vibration response analysis can be carried out based on the finite element model. From analysis of the above simulation results, we can get the weak parts of the structure and modify the topology structure to improve the mechanics characteristics. By some cycles of topology optimization by human-computer interaction, the structure will be better performed under the dynamic environment. Secondly, after the topology optimization by human-computer interaction, size optimization by computer is executed to find the best size for the structure to reach the best objective under the constraints. Thirdly, we will check the dynamic stress and other parameters to make sure that it can satisfy the requirement under the dynamic environment.

As the above mentioned, we separate the constraints to three phases to consider including frequency constraints, dynamic response acceleration constraints, and dynamic response stress constraints [13]. In the topology optimization stage by human-computer interaction, frequency constraints are the main constraint condition while the dynamic response acceleration constraints are used to prove the effectiveness of the topology modify. In the size optimization stage by computer, dynamic response acceleration constraints and frequency constraints are the constraints while the mass of the structure is the objective. In the check stage, dynamic response stress constraints are the constraint condition, we can use the shape optimization to reduce the concentrated stress if the stress is too large to satisfy the requirement. Human work not only plays a part in the topology optimization phase, but also in the decisions of whether or not the results are satisfied with the optimum scheme [14]. Figure 1 is the flow chart of the human-computer interaction structural optimization method under dynamic response constraints.

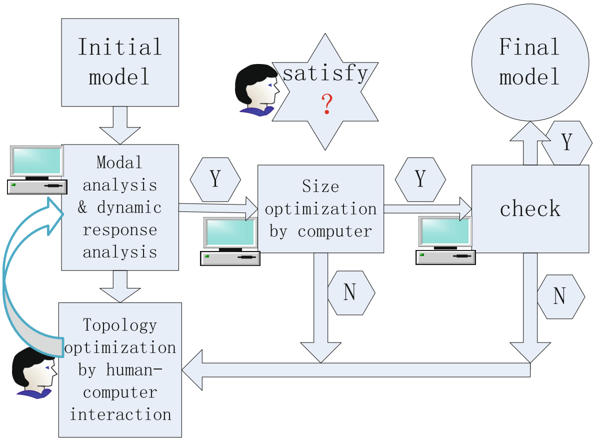


Fig. 1. Flow chart of human-computer interaction structural optimization method

# 3 Structural Optimization of an Aerospace Assembly Using the Human-Computer Interaction Method

## 3.1 Problem Description

The aerospace assembly was including external framework and internal function products. As the internal function products was hard to modify, then the optimization concerned on the external framework which was consist of thin-walled beams. So the finite model of the frame was divided by two dimension grids while the internal function products were divided by three dimension grids. The design variable was the topology variable and the size variable, and the objective of the optimization was minimizing the mass under the dynamic response constraints, which included stiffness requirements and strength requirement. The stiffness requirement was that the first integral vibration frequency of the assembly was not less than 60 Hz and the acceleration magnification of the cared nodes was less than 5, while the strength requirement

**Table 1.** Sine test conditions of the aerospace assembly

| Parameters (identification level) | Frequency(Hz) | | | |
|---|---|---|---|---|
| | 4～10 | 10～17 | 17～75 | 75～100 |
| Amplitude 0～p | 13.09 mm | 3.22 g | 6.86 g | 4.13 g |
| Loading direction | Three directions | | | |

was that the stress of the assembly was lower than the yield limit of the material (2Al2, 280 MPa) under given sine test conditions. The problem could be described as Eq. (1). The sine test conditions could be described as Table 1.

$$\begin{cases} \text{find best(topo,size)} \\ \text{min Mass} \\ \text{s.t. freq} \geq f_0 \\ \quad \text{freq\_acce(out)/freq\_acce(in)} \leq a \\ \quad \text{freq\_stress} \leq \tau_0 \end{cases} \tag{1}$$

In this model, first integral vibration frequency ($f_0$) was set as 60 Hz, and magnification of dynamic response acceleration (a) was set as 5, yield limit of the material ($\tau_0$) was 280 MPa.

### 3.2 Topology Optimization by Human-Computer Interaction

The finite element model was created by HyperMesh software while the mesh size was set as 5 mm, the external frame was meshed to 2d grid, while the internal functions products were meshed to 3d grid and finally the finite element model could be described in Fig. 2. Once the finite element model was created, and then modal analysis and vibration response analysis was being carried out based on the finite element model. From analysis of the above simulation results, we got the weak parts of the structure and modified the topology structure by human-computer interaction work to improve the mechanics characteristics. By some cycles of topology optimization by human-computer interaction, the structure was better performed under the dynamic environment. Figure 3 was the first vibration feature of the four topology structure by human-computer interaction topology optimization. The initial model was structure a, the first integral vibration frequency of a was 42.3 Hz, which was less than the objective that was 60 Hz. Worse still, the vibration feature of cared function products was too bad to satisfy the requirements. So the cared function products position was transferred to other location based on human-computer interaction style as structure b and the first integral vibration frequency increased from 42.3 Hz to 44.2 Hz, and the vibration feature improved a lot. However, it still could not satisfy the final requirements. So we added structure b a beam to structure c, and the first integral vibration frequency of the aerospace model increased from 44.2 Hz to 45.8 Hz. Finally, we added structure c some braces to structure d by human-computer interaction topology optimization, and the first integral vibration frequency improved from 45.8 Hz to 58.2 Hz.

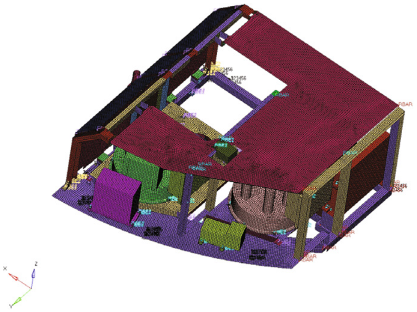
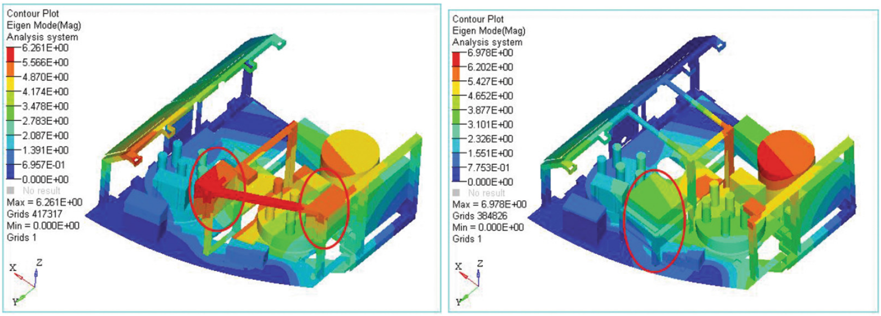
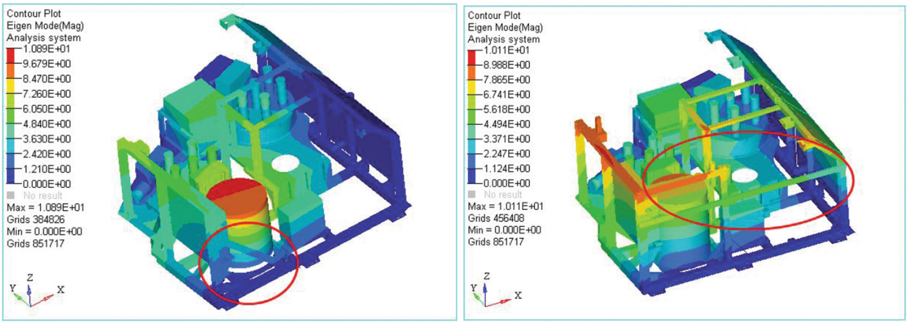


**Fig. 2.** The finite element model of the initial aerospace assembly



Topo a 42.3Hz Topo b 44.2Hz



Topo c 45.8Hz Topo d 58.2Hz

**Fig. 3.** The first vibration feature of the four topology structure

To get a better look at the effect of the topology optimization by human-computer interaction style, Table 2 listed the parameters change of four topology structure by human-computer interaction topology optimization. And Fig. 4 provided the graph of acceleration magnification (node 516535) of four topology structure by human-computer interaction topology optimization. The first integral vibration of the assembly changed from 42.3 Hz (topology structure a) to 58.2 (topology structure d), while the magnification acceleration of node 516535 changed from 6.18 to 4.91, and the mass of

**Table 2.** Parameters change chart of four topology structure

| Parameters | Topo a | Topo b | Topo c | Topo d | Rate change a & d |
|---|---|---|---|---|---|
| First integral vibration frequency/Hz | 42.3 | 44.2 | 45.8 | 58.2 | +37.6 % |
| Magnification of acceleration (node 516535) | 6.18 | 6.00 | 5.12 | 4.91 | −20.6 % |
| Mass of the frame/kg | 17.49 | 17.25 | 17.57 | 17.93 | +4.7 % |

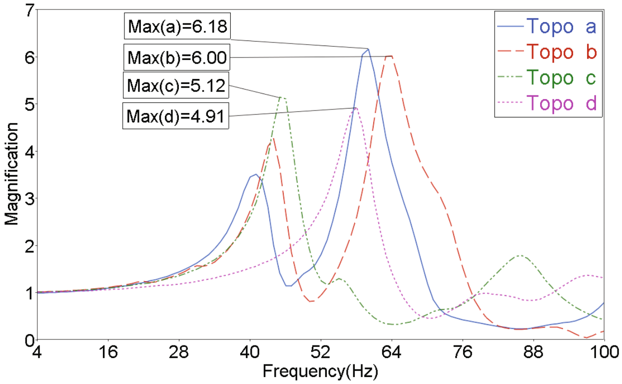


**Fig. 4.** Acceleration magnification of four topology structure (node 516535)

the frame changed from 17.49 kg to 17.93 kg. The vibration feature improved a lot from topology structure a to topology structure d. However, the mass of the frame increased, which was not what we want.

### 3.3 Size Optimization by Computer

Size optimization by computer was executed to find the best size for the structure to reach the best objective under the dynamic environment constraints [15, 16]. The objective of the optimization was minimizing the mass under the dynamic response constraints and the design variable in this phase was size variable. Considering of all factors, we chose the following ten size variable and every variable had its maximum limit and minimum limit. After 16 iterations, the results tent to be convergent. Table 3 was the initial value and the final value, the maximum limit and minimum limit. Figures 5 and 6 were respectively iteration graph of the objective function and constraints.

The first integral vibration frequency increased from 58.2 to 59.7 after size optimization by computer, and acceleration magnification of node 516535 dropped from 4.91 to 4.62, while the mass of the frame dropped from 17.93 kg to 17.44 kg. Combined the topology optimization by human-computer interaction and size optimization by computer, the simulation results can be drawn as follows. After the human-computer interaction optimization, the change of cared parameters by simulation results could be described as Table 4. From Table 4 we could see, the first integral vibration of the aerospace assembly increased as much as 41.1 %, and acceleration magnification of cared node dropped as much as 25.2 %, and the mass of the frame also dropped as we expected before.

**Table 3.** Initial value and final value, maximum and minimum limit of size variable

| Number | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial value/mm | 5 | 4 | 4.3 | 8 | 9 | 4.4 | 10 | 2 | 6 | 3 |
| Max and min limit /mm | 6 | 5 | 5 | 10 | 12 | 5 | 15 | 3 | 8 | 4 |
| | 4 | 3 | 3 | 6 | 6 | 3 | 5 | 1 | 4 | 2 |
| Final value/mm | 5.66 | 3.81 | 3 | 7.72 | 6 | 3 | 5 | 1.66 | 4 | 2 |

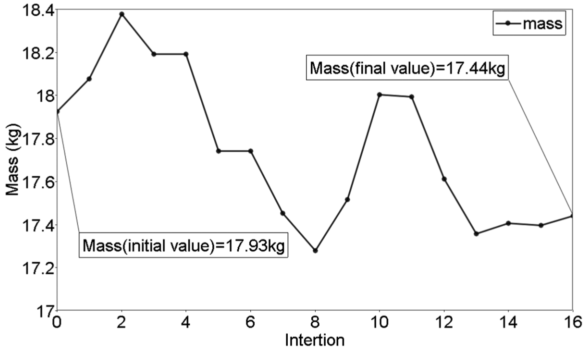


**Fig. 5.** Iteration graph of objective function

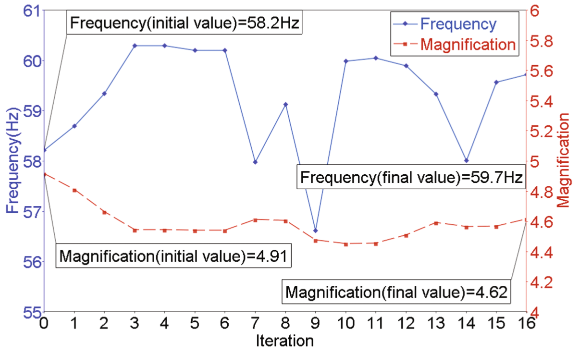


**Fig. 6.** Iteration graph of constraints

**Table 4.** Changes of cared parameters by simulations results after human-computer interaction optimization.

| Parameters | Initial value | Optimization results | Rate change |
|---|---|---|---|
| First integral vibration frequency/Hz | 42.3 | 59.7 | +41.1 % |
| Magnification of acceleration(node 516535) | 6.18 | 4.62 | −25.2 % |
| Mass of the frame/kg | 17.49 | 19.44 | −0.3 % |

### 3.4 Check of Dynamic Response Stress

To make sure that the structure after optimization can satisfy the requirement under dynamic response constraints, especially for the dynamic response stress, we made vibration response analysis based on the given dynamic load condition and the stress cloud of the assembly on given dynamic loads could be described as Fig. 7. The results showed that the maximum of the Von Mises was located in the installation holes of the assembly and the maximum value was 171.2 MPa, which was less than the yield limit of the material (280 MPa). The results indicated that the dynamic response stress could satisfy the requirements.

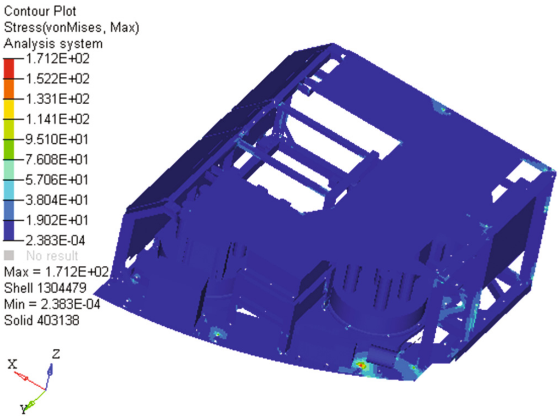


**Fig. 7.** The stress cloud of the assembly on given dynamic loads (60 Hz)

### 3.5 Experimental Verification

The final product was produced based on the final simulation optimization results. And vibration environment experiment was established on the 10t platform vibrator. In considering of keeping secret, the figure of experimental design will not be given. From the vibration experiment, the following data could be achieved that the first vibration frequency experimental result of the aerospace assembly was 60.2 Hz, while the simulation result was 59.7 Hz. The magnification acceleration of node 516535 was 4.50, while the simulation result was 4.62. And the mass of the frame was 19.35 kg,

**Table 5.** Comparison of the simulation results with the experimental results

| Parameters | Simulation results | Experimental results | Relative error |
|---|---|---|---|
| First integral vibration frequency/Hz | 59.7 | 60.2 | 0.8 % |
| Magnification of acceleration(node 516535) | 4.62 | 4.50 | 2.7 % |
| Mass of the frame/kg | 19.44 | 19.35 | 0.5 % |

while the optimization result was 19.44 kg. Also experimental design proved that the dynamic response stress could satisfy the requirements. Table 5 listed the comparison of the simulation results with the experimental results.

## 4 Conclusion

Combining with the advantages of human and computer in complex structural optimization, the proposed human-computer interaction method could make a good performance in complex assembly's optimization. It also provided new ideas for structural optimization under dynamic response constraints to solve practical problems. In this paper the aerospace assembly could not satisfy the requirement under the dynamic response constraints primitively. But after the human-computer interaction structural optimization, the final structure could satisfy the dynamic environment requirement and results showed that first integral vibration frequency raised 41.1 % (from 42.3 Hz to 59.7 Hz) and magnification of acceleration dropped 25.2 % (from 6.12 to 4.62) while the mass remained essentially unchanged (from 17.49 kg to 17.44 kg). Also the experimental results compared with the simulation results showed that the relative error was less than 5 %, which proved the effectiveness of the simulation design. The human-computer interaction method might provide a reference for similar products that are not limited to aerospace field.

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