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Parametric modeling and structural optimization of a conventional island dual-output nuclear gearbox

Shuai Liu*. Fuhao Liu
Qingdao University of Technology, Qingdao 266000, China
Email: 2758026559@qq.com

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Abstract

With the development of nuclear energy, the number of nuclear power plants established in the world is increasing, and the conventional island nuclear gearbox plays an important role in the whole nuclear power plant system, in order to reduce the construction cost of the nuclear gearbox and improve the economy, the optimization design of the nuclear gearbox is carried out. In this paper, the parametric modeling of the nuclear gearbox by ANSYS APDL, as well as the design of the previous internal single output planetary wheel system re-ducer, improved to a double output reducer, which can reduce the use of nuclear gearbox body. The parametric model of the whole case is established by using APDL language programming, and the whole model is established automatically by writing macro files and then reading the program into ANSYS software, which provides great convenience for the future static and dynamic analysis, and the case is structurally optimized by using AMSYS APDL to reduce the mass.

Keywords

Gearbox; Structural optimization; planetary reducer; Parametric modeling

1. Introduction

Along with the continuous development of science and technology, the number of high-power gearboxes applied in nuclear power plants is also increasing.[1] Reduction gearbox body as an important component in large machines and equipment, the design as well as the style is also more and more [2]. It is characterized by compact structure, small size, small rotational inertia, and wide application. The design of high-power nuclear power gearboxes is bulky and heavy, with a lot of material allowance, and it is necessary to carry out topology optimization and structural optimization of the structure to reduce the quality of the material and improve the economic efficiency under the safety analysis of the static characteristics of the gearbox[3].

2. APDL structural optimization design process analysis

ANSYS is a very widely used finite element analysis software, which is widely used in mechanical aerospace and aviation and other fields, and its finite element analysis process mainly consists of three steps, which are: establishing the analytical model and applying the boundary conditions, solving the calculations and analyzing the results in three steps.

APDL is the abbreviation of ANSYS Parametric Design Language. It is a scripting language that builds analytical models by means of parametric variables, and APDL parametric modeling is a prerequisite for structural optimization[4]. The initialization of analysis parameters is to specify initial values for relevant parameters in the analysis model, and the parameters are defined to facilitate the next step of parametric model building. A parametric mathematical model is built, and the parameters in the model temporarily take the initial values defined at the beginning above.

After that, the loading solution is performed to execute the solution of the primary structural analysis. Performing a structural analysis is a more important part of the structural optimization design, because the values of the state variables and the target variables are implicit functions of the design variables, which cannot be obtained directly and need to be solved by the finite element solution to obtain the values, so it is necessary to perform a structural analysis to extract the results of the parameters[5].

Next, the optimization analysis file is formed. Formally enter the structural optimization module OPT of ANSYS Mechanical APDL, confirm the analysis file, confirm the optimization variables (design variables, state variables, target variables) and their settings (value ranges, constraints), and then execute the optimization analysis with the help of optimization algorithms and search tools, and ultimately output and view the results of the optimization design[6].ANSYS Mechanical The optimization process in APDL can be summarized as follows[7]

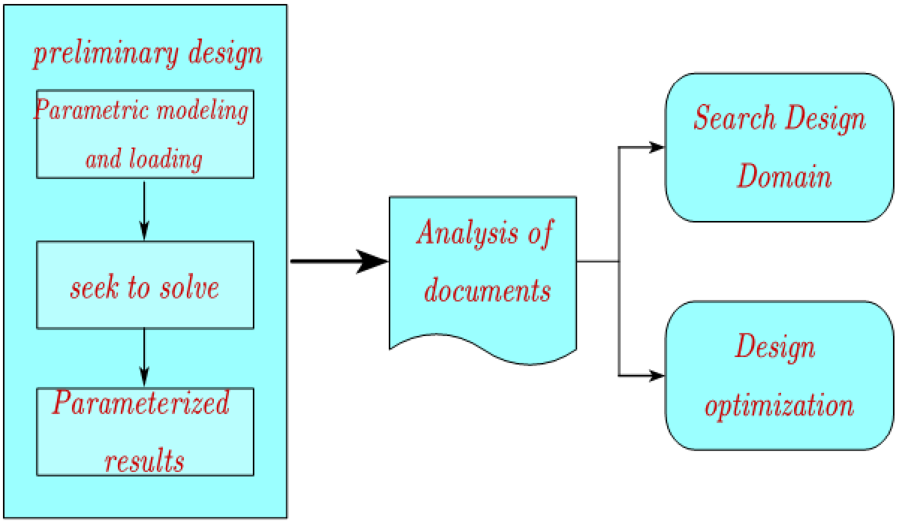

Figure 1. Optimization Analysis Flowchart

3. Structural design of gearbox case and reducer

3.1. Box structure design

The structure of this nuclear power gearbox is mainly composed of five parts: upper end cover, input bearing housing, support disk, output bearing housing and planetary wheel system transmission part. The input part of the power is the motor, which carries out power input through the input shaft, and runs through the traveling pump. Planetary reducer, to achieve the role of reducing speed and increasing torque, the output shaft end connected to the water pump, thus driving the operation of the water pump. The box is fixed and restrained by the lugs on the support disk. The transmission device is a two-stage planetary wheel system, is an input and two outputs. The SolidWorks 3D exploded view of this vertical nuclear gearbox is shown in Figure 2.

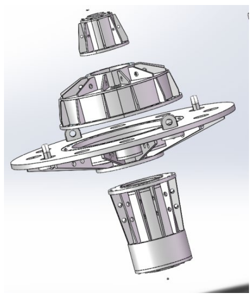

Figure 2. three-dimensional exploded view

3.2. Reducer structure design

Figure 3 and the table below show the gearbox transmission sketch and data parameters.

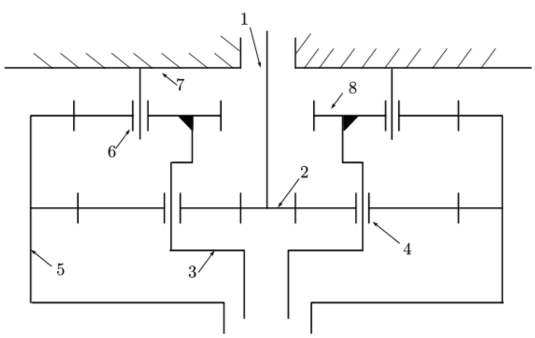

Figure 3. Transmission principle of two-stage double output reducer

1-Input shaft; 2-High-speed stage sun wheel; 3-High-speed stage planetary carrier; 4-High-speed stage planetary wheel; 5-Inner gear ring; 6-Low-speed stage planetary wheel; 7-Low-speed stage planetary carrier; 8-Low-speed stage sun wheel

Table 1. Parameters of each gear of the high-speed stage of the two-stage double-output reducer

high speed	solar plexus chakra	internal ring	planetary wheel
Number of teeth	28	86	29
modulus	16	16	16
quantities	1	1	3

Table 2 Parameters of each gear in the low-speed stage of a two-stage double-output reducer

low speed	solar plexus chakra	internal ring	planetary wheel
Number of teeth	38	86	24
modulus	16	16	16
quantities	1	1	4

3.3. Reducer strength check

Transmission Ratio Calculation

$$i_{23} = {w_2}/{w_3} = {z_8}/{z_2}(1+{z_5}/{z_8})+1 \tag{1}$$

$$i_{25} = {w_2}/{w_5} = -{z_5}/{z_2}(1+{z_5}/{z_8})-{z_5}/{z_8} \tag{2}$$

Concentricity condition calibration

$$z_5 = z_8 + 2z_6 \tag{3}$$

$$z_5 = z_2 + 2z_4 \tag{4}$$

Neighbor Condition Calibration

$$\left.\begin{array}{c} l_b > 2r_{ab} \\ 2a'_{ab}\sin {\pi}/{n_p} > d_{ab} \end{array}\right\} \tag{5}$$

r_{ab} 、 d_{ab} - Radius and diameter of the apex circle of the teeth of the planetary wheel b; n_p - Number of planetary wheels; a_{ab} - a, b Center distance of gear meshing pair; l_b - The distance between the centers of two adjacent planetary wheels.

Calibration of homogeneous conditions

$$z_a + {z_c}/{n_p} = A(\text{Integer}) \tag{6}$$

According to the formula, the reducer satisfies the concentric condition, the neighboring condition, and the homogeneous condition

4. Force analysis of the box

In the working process of the gearbox, the main force of the box comes from the bearings, and the force transmitted by the shaft connected by the bearings acts on the bearing housing. Calculation of the box force first need to calculate the meshing force between the gears. Then, according to the principle of Newton's third law, the force on each shaft is analyzed. Ultimately, the magnitude and direction of the support reaction force and torque applied to the bearings and internal gears connected to the box are derived. In this paper, the support and reaction forces and torque of the bearings and internal gears connected to the box by the transmission system are calculated separately by the operating conditions under rated operating conditions and ignoring the effects of friction and gravity.

4.1. Case Material Data

The material of the support disk of the box is Q345, and the material of other parts of the box is Q235; the power of the motor at the input end is 5900 KW, the input speed is 994 RPM, and the input torque is 56679 Nm. The mass of the box is 28.571 tons

4.2. Calculation of forces on gear teeth

In planetary gearing, the force analysis and calculation of a meshing gear pair is the same as that of an ordinary fixed-axis gearing. In cylindrical gearing, if the effect of friction between the teeth is ignored, the normal force F_n can be decomposed into the following three forces, namely：

tangential force

$$F_t = {2000T_1}/{d_1} \tag{7}$$

radial force

$$F_r = {F_t \tan \alpha_n}/{\cos \beta} \tag{8}$$

axial forces

$$F_a = F_t \tan \beta \tag{9}$$

T_1 -Torque transmitted by a pinion in a meshed gear pair; β -Helix angle on helical gear indexing circle; d_1 -Pinion indexing circle diameter; α -Indexing Circle Pressure Angle;

Calculate the driveline torque at rated operating conditions

Under the condition that the nominal power p and synchronous speed n of the prime mover (motor, etc.) are known, the torque T transmitted by its input parts can be calculated according to the following formula, i.e.

$$T_1 = 9549 {P_1}/{n_1} \tag{10}$$

Formula: p_1 -Nominal power transferred by the input; n_1 -Rotation speed of input parts

4.3. Force on the box

According to the formula to calculate the meshing force and torque between the gears, the input and output shaft force analysis, according to the force balance equation can be obtained under the rated working conditions of the box force size. Considering the gravity of the transmission system, the box load boundary consists of the motor's traction torque transferred to the gearbox excitation load part of the composition, according to the results of the bearing support reaction force calculation in this section, it can be seen that the motor torque transferred to the gearbox excitation load is only the torque T_b.

$$T_b + T_{\text{Output 1}} + T_{\text{Output 2}} + T_1 = 0 \tag{11}$$

5. Finite Element Analysis

5.1. Parametric modeling

The four major components of the box and the planetary drive train are parametrically modeled and assembled using APDL parametric language. The case is modeled using solid92 cells with a mesh size of 60mm and free meshing, and the planetary gearbox is modeled using solid185 cells for free meshing.

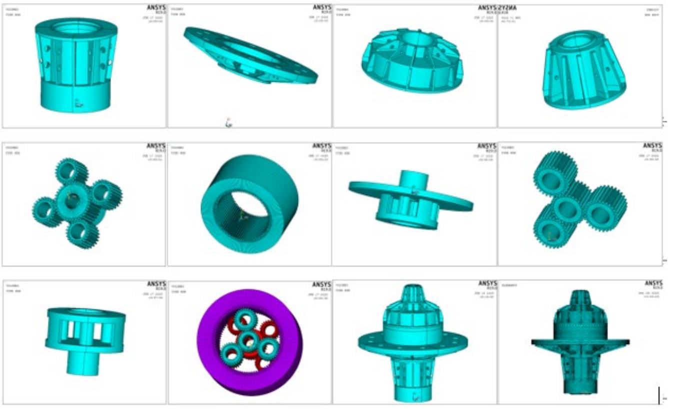

Figure 4. Finite element 3D modeling

5.2. Static analysis

The finite element model of the gearbox created by ANSYS APDL was taken and the boundary conditions and constraints computed above were applied to the box.

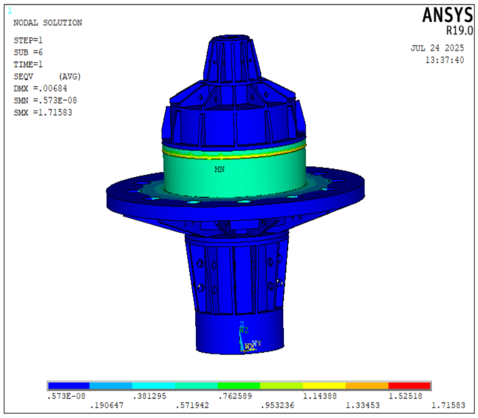

Figure 5. stress map

According to the hydrostatic analysis of the shell yielded stress cloud diagram, can clearly see the size of the stress on the shell, the size of the stress on the shell is less than the yield strength of the material, so it meets the requirements of the strength, in preparation for the subsequent optimization of the structure.

5.3. Modal analysis

Modal analysis can derive the intrinsic frequency and the corresponding vibration mode of the structure, which is the basis of dynamic analysis. Obtain the first six orders of modes of the box to see the change of vibration mode of the box in the first six orders.

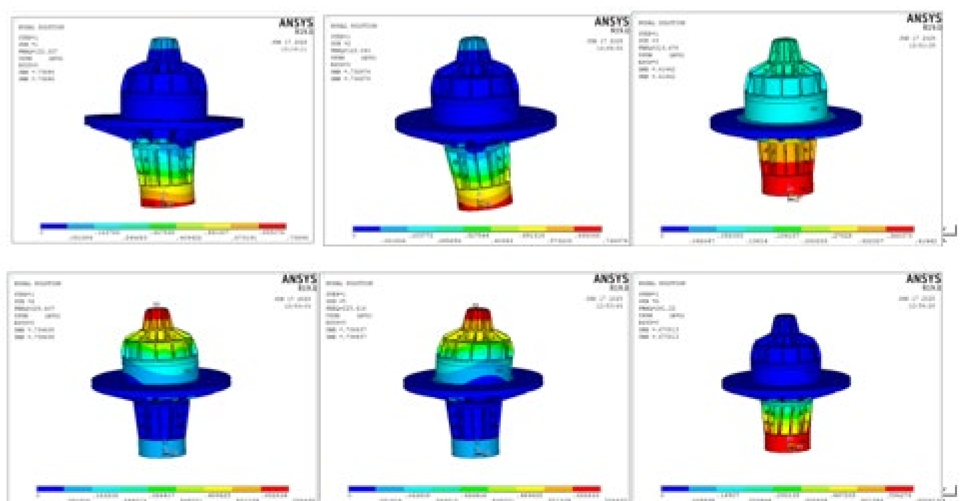

Figure 6. modal cloud diagram

Table 3. Shape analysis of the first six modes

ordinal number	frequency	Shape Description
first stage	122.33	The lower part of the box is flat along the y-axis
second stage	12.34	The lower part of the box is flat along the x-axis

third stage	213.68	Rotation of the box as a whole along the z-axis
fourth order	225.41	The upper part of the box is flat along the y-axis
fifth order	225.42	The upper part of the box moves flat along the x-axis
sixth order	241.22	Rotation of the lower part of the box along the z-axis

6. Structural optimization of the box

The design variables, objective variables and constraints are the main elements of the optimal design of a structure, and the general expression of its mathematical model is[8]:

$$f = f(x) \to \min \tag{12}$$

$$X = \left[x_1, x_2, \cdots, x_n\right]^T \tag{13}$$

$$1.5 \le g_i(x) \le 1.8 \qquad i = 1, 2, \cdots, m \tag{14}$$

The structural optimization is carried out using the zero-order algorithm in ANSYS APDL, which allows a quick search of the defined range. In this paper, the dimensions of 17 shells are set as the design variables, the mass as the objective variable, and the strength stress magnitude of the shells as the constraint variable, and the iterative operation is run for 10 times. The following figure shows the range change of the target variables during the iteration process.

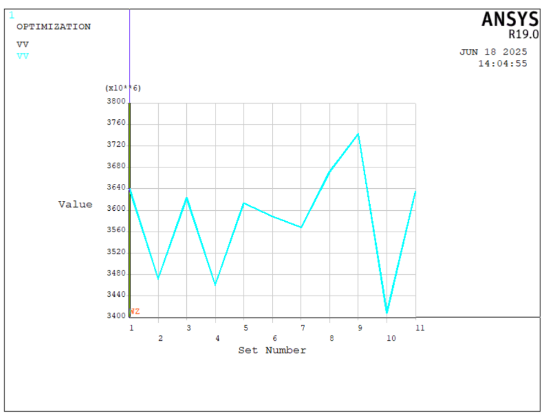

Figure 7. Plot of iterative changes in the objective function

According to the results of the final iterative change, the optimized mass is 27.255 tons, a 4.6% weight reduction

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