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Study on Optimization Design of Pressure Hull for Underwater Vehicle

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Abstract**—**In order to improve the efficiency and accuracy of the pressure hull structure, optimization of underwater vehicle based on response surface methodology, a method for optimizing the design of pressure hull structure was studied. To determine the pressure shell of five dimensions as a design variable, the application of thin shell theory and the Chinese Classification Society (CCS) specification was carried on the preliminary design. In order to optimize variables of the feasible region, different methods were studied and implemented such as Opt LHD method (to determine the design test sample points in the feasible domain space), parametric ABAQUS solution for each sample point response, and the two-order polynomial response for the surface model of the limit load of structures. Based on the ultimate load of the structure and the quality of the shell, the two-generation genetic algorithm was used to solve the response surface, and the Pareto optimal solution set was obtained. The final optimization result was 41.68% higher than that of the initial design, and the shell quality was reduced by about 27.26%. The parametric method can ensure the accuracy of the test and improve the efficiency of optimization.

Keywords**—**Parameterization, response surface, structure optimization, pressure hull.

I. Introduction

UNDERWATER vehicle is an important tool to study and explore the ocean field. The safety and the overall performance of the underwater vehicle are directly influenced by the quality of the design and quality of the instrument. Many scholars at home and abroad, in order to optimize the design of the structure, will focus on the study of the limit load and put forward the approximate model and the finite element method of the underwater hull structure optimization. In this paper, the response surface model and the genetic algorithm are introduced to optimize the structure design of pressure vessel shell literature [1]. From Shanghai Jiao Tong University, Chen Luyun et al. applied ISIGHT integrated PATRAN/NASTRAN to optimize the dynamic design of the ring stiffened cylindrical shell [2]. Harbin Engineering University and Yang Zhuoyi have done a lot of research on the optimization of Submersible Pressure Hull [3]-[7]. However, there are still some shortcomings. Based on the above research and the literature [8] data, PYTHON, optimization software ISIGHT and finite element software ABAQUS were used as tools. An excellent ring ball column combined pressure shell structure was produced based on parametric modeling, limit load analysis, response surface model and genetic algorithm for multi-objective optimization. It solves the problem that the optimization variables in the optimization process of the approximate model and the finite element method need to be modeled and calculated iteratively. At the same time, ABAQUS has excellent ability to solve nonlinear problems to ensure the accuracy of the ultimate load calculation.

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II. Shell Structure and Modeling

A. Structure Form Determination

In this paper, the underwater vehicle shape form is taken from the literature [1] with design depth of 400 m, pressure hull form is ball column combination (see Fig. 1) and the shell material is high strength steel (material parameters are shown in Table I). It can obtain a mass displacement better than that in the use of materials improved efficiency and stability; on the other hand, it reduces the movement resistance and manufacturing difficulty, enhances the inner space utilization rate. Using the thin shell theory and CCS specification [9] determined the optimization variables were: pressure shell wall thickness, rib thickness, parallel segment length, radius, cabin shell rib height, ring rib number N and its feasible range (see Table II)

TABLE I
Parameters of High Strength Steel

Elastic Modulus E/MPa	Poisson Ratio v	Prop. Limit σp/MPa	Yield Limit σs/MP	Ultimate strengthσ_b/MPa
$1.96 x 10^5$	0.3	588	785	820

TABLE II
The Feasible Range of Optimization Variables

	y_1	y_1	y_1	y_1	y_1	N
Initial value	10	6	5	0.23	40	17
Variable range (mm)	8-12	4-8	3400-6600	0.23-0.29	3-5	17

B. Parametric Finite Element Method

The mechanical properties of casing pressure mainly include two aspects of strength and stability. The problem of modern stability is mainly to study the buckling state of engineering practice, but also can represent the nonlinear buckling problem of critical buckling load of the lower limit. Therefore, this paper applies the ABAQUS finite element analysis software to simulate the structure of the nonlinear problem. In this paper, the Shell model is used to construct the 3D model in the ABAQUS shell. Coordinate setting: X-axis of beam direction, left side is positive; Y-axis depth direction, upward is positive; Z-axis for the direction, to bow to it. The 3D model and coordinate system are shown in Fig. 2. The boundary conditions can be used to control the displacement and rotation angle of the pressure hull, and the angular displacement constraint is not necessary. We do not need to use angular displacement constraints, the boundary conditions are given in Table III.

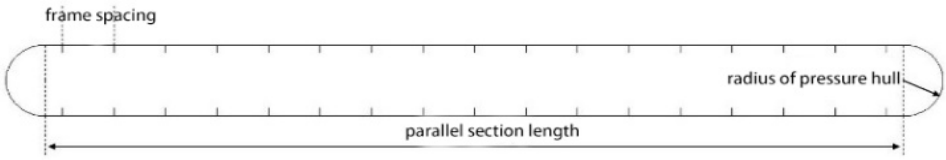

Fig. 1 Pressure hull structure of underwater vehicle

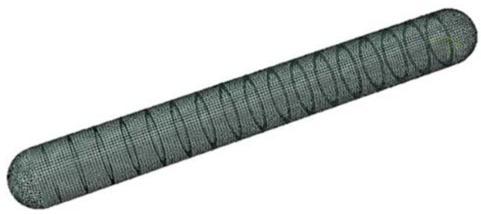

Fig. 2 Finite element model

TABLE III
THE BOUNDARY CONDITIONS OF THE PRESSURE HULL STRUCTURE

Position	Linear displacement constraint		
	δx	δy	δz
X axis and cylindrical shell intersection	—	Cons.	Cons.
The pressure hull fwd endpoint	Cons.	Cons.	—
The pressure hull aft endpoint	Cons.	Cons.	—

C. Calculation Principle

Calculated using the arc length method (Riks method) combined with Newton-Raphson method for solving the nonlinear buckling problem [9]. Firstly, linear buckling analysis is done, and then the arc length method and the initial deflection on the nonlinear buckling analysis considering the nonlinear effect of the material and geometry. Critical buckling load of the underwater vehicle is the load numerical curve corresponding to the highest load factor curve. The specific calculation process of Riks method is as follows:

1. Internal nodal stress matrix:

$$I^N = \int_V \beta^N : \sigma dV \tag{1}$$

$$K^{NM} = \frac{\partial I^N}{\partial u^M}$$

2. Check the balance equation:

$$R_i^N = \left(\lambda_0 + \Delta\lambda_i\right) P^N - I^N \tag{2}$$

If the values are very small, it indicates that the results converge, if not one has to converge the equation.

$$K^{NM}\left\{v_i^M ;\ c_i^M\right\} = \left\{P^N ;\ R_i^N\right\} \tag{3}$$

The components of the two directions are PN and RN, and the displacement components in the two directions are v_i^N、c_i^N.

3. Vector will be ($\tilde{v}_i^N$;1) scaling, and add it to ($\tilde{c}_i^N$; ρ_i) (among $\rho_i = R_i^N P^N / \bar{P}^2$),to get the equation:

$$\left\{\left(0;-\rho_i\right)+(\tilde{c}_i^N;\rho_i)+\mu\left(\tilde{v}_i^N;1\right)\right\}:\left(\tilde{v}_0^N;1\right)=0 \tag{4}$$

Therein:

$$\mu = -\frac{\tilde{c}_i^N \tilde{v}_o^N}{\tilde{v}_i^N \tilde{v}_o^N + 1}$$

Solution of Ai: $\left(u_0^N + \Delta u_i^N + c_i^N + \mu v_i^N ; \lambda_0 + \Delta\lambda_i + \mu\right)$

4. Next Iteration:

$$\begin{aligned}\Delta u_{i+1}^N &= \Delta u_i^N + c_i^N + \mu v_i^N \\ \Delta\lambda_{i+1} &= \Delta\lambda_i + \mu \\ i &= i+1\end{aligned} \tag{5}$$

Repeat step 1. ABAQUS will make additional corrections after every iteration.

III. PARAMETRIC FINITE ELEMENT TEST

A. Experimental Design

In order to construct the response surface model, it is necessary to design the experiment. By selecting the test points reasonably and using fewer points to describe the test space, the functional relationship between the optimal variables and the response is obtained. The Latin square method is widely used in the computer simulation of the full factorial experiment and orthogonal test. This paper puts forward the optimal frequency theory and Bayesian method based on Latin hypercube (Opt LHD). This method is the improvement of Latin square design taking into account the uniformity of the space filling when compared at the same time. If the test design has 'n' test points, 'm' test factors, then the experimental design matrix can be formed, $X = [X_1, X_2, \cdots, X_n]^T$ and the row of the matrix $X_i = [X_{i1}, X_{i2}, \cdots, X_{in}]$ represents the experimental analysis.

In this paper, the two-order fitting response surface is used, and the initialization process needs at least one sample point $(M+1)(M+2)/2$, M is the number of factors, that is, the experiment needs at least 21 samples. Considering the computational efficiency and the engineering feasibility of the optimization parameters, each factor is divided into 81 parts in the design space, that is, the level of the 81 levels, each level of 0-2 times, the results of the 81 groups of test programs. The results of the scheme and the corresponding calculation are shown in Table IV.

B. Parametric Drive

In the optimization, design of the pressure hull structure, the general modeling method needs iterative modeling. The calculation efficiency is low, and the manual operation is prone to error. Parameterization is also called parameter riven, that is, the establishment of graphical constraints and geometric relations and the corresponding relation of the parameter size is directly controlled by the change of the size parameter value Variation of body model [10]-[12]. Its essence is to use a set of numbers to describe the physical model. The modification of the model is realized by digital modification. By means of parameterization, the flow chart of the finite element calculation is shown in Fig. 3.

In the process of running the ABAQUS software, In the process of running the ABAQUS software, the background kernel will automatically record the default command entered in ABAQUS/CAE in the Python scripting language compiled in the *.py file. Through the *.py text, the development of the code will help in the implementation of the parametric model configuration, load and boundary condition setting, grid partition, analysis step setting, strength and buckling analysis, data reading and optimal output. On this basis, the batch file is called by ISIGHT software robot *.bat batch operation of the above processes.

After calculating the precision and scale of calculation, this paper uses 25 mm x 25 mm mesh and 8-node linear hexahedron reduced integration unit (C3D8R) with calculated depth hj=600 m and calculated load Pj=6 MPa for strength check. Without considering the depth under the condition of pressure difference, the 100-Pa pressure gauge is applied to the load calculation of critical buckling pressure Pcr1.

Using the Riks method, the nonlinear buckling analysis of the model is carried out to obtain the variation curve of the load factor of the structure (Fig. 4).

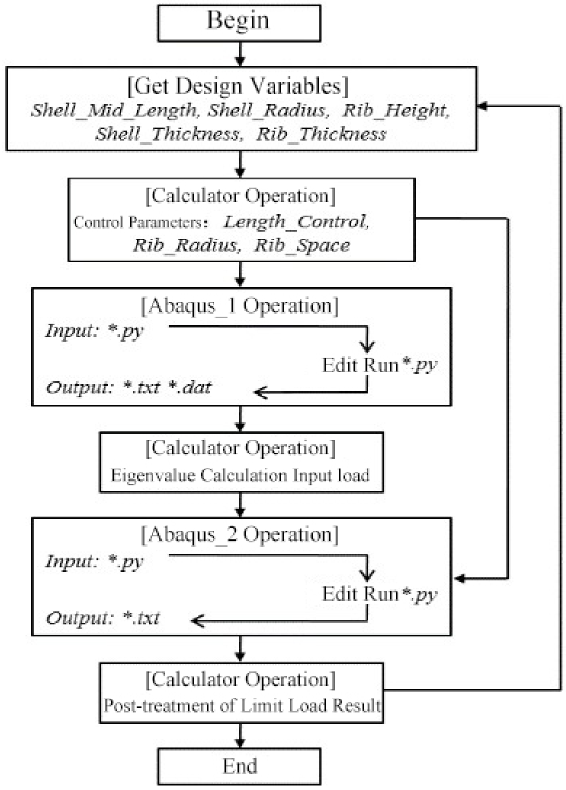

Fig. 3 Flow chart of parametric drive of pressure hull

Through the ISIGHT integrated ABAQUS software for the above calculation, the response value of the test design is shown in Table IV.

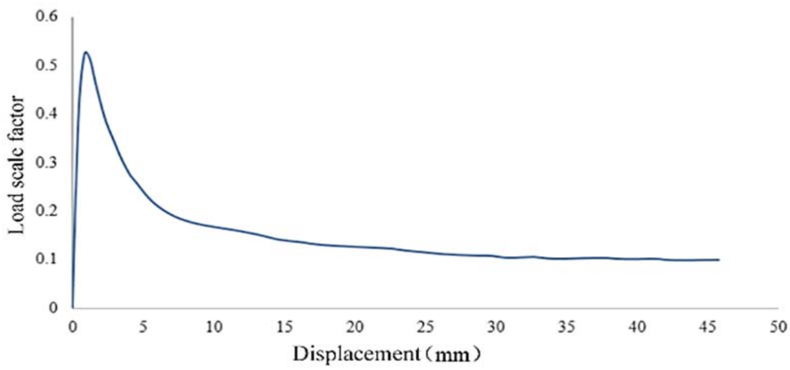

Fig. 4 Load scale factor curve

TABLE IV
RESPONSE VALUE OF PRESSURE HULL DESIGN OF UNDERWATER VEHICLE

	T (mm)	Rt (mm)	L (m)	R (mm)	Rh (mm)	σ (MPa)	P_{cr2} (MPa)
1	9.15	7.45	3.56	280.25	41.75	169.65	15.49
2	8.45	5.65	5.92	242.75	31.50	155.64	5.35
3	11.7	4.30	4.68	251.75	34.75	115.92	14.27
4	9.75	7.05	5.48	253.25	30.25	138.19	7.518
…	…	…	…	…	…	…	…
78	8.10	6.90	4.24	262.25	47.25	177.04	17.38
79	8.80	4.35	5.16	248.00	48.00	153.26	18.44
80	9.00	7.10	4.08	233.75	46.75	141.56	24.93
81	11.0	4.40	3.84	257.00	47.50	129.99	27.96

IV. RESPONSE SURFACE MODEL

A. The Two-Order Polynomial

The response surface model (RSM) is a comprehensive analysis of test technology for experimental design and statistics. The order response surface method with its concise expression is the most commonly used design variable combined with the corresponding mapping relationship between the two. It is widely used for mathematical expressions:

$$\hat{F}(\mathrm{x}) = a_0 + +\sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} c_{ii} x_i^2 + \sum_{1\le i\le j\le N}^{N} d_{ij} x_i x_j \tag{6}$$

The response F (x) surface approximation and xi is the design variable, and N is the number of design variables. And a_0, b_i, c_{ii}, d_{ij} are the constants, which are cross terms of the undetermined coefficient. The method of Replacement (Residual Sum of Squares), which is the smallest and the most objective of the least squares (Sequential), is chosen as the method to select the response surface key to improve the precision and quality of the model. Through the above methods, the design variables and the objective function of the two-order polynomial regression are as follows:

$$\begin{aligned} p_{cr2} = {} & -17015905 + 4311265120y_1 + 719509531y_2 - 4395181y_3 - 101761294y_4 + 1398762255y_5 + 23800059591y_1^2 \\ & + 54378147426y_2^2 + 630852y_3^2 + 639530092y_4^2 + 6522674219y_5^2 + 1071075186y_1y_2 - 255801619y_1y_3 - 17322425811y_1y_4 \\ & + 70710508281y_1y_5 + 8186569y_2y_3 - 5923550180y_2y_4 + 2734473751y_2y_5 + 11216630.611084y_3y_4 - 116821315y_3y_5 - 4922245194y_4y_5 \end{aligned}$$

$$\begin{aligned} \sigma = {} & 218518267 - 36804062006y_1 - 476319019y_2 - 2731255y_3 + 877241393y_4 + 204879213y_5 + 1776575216963y_1^2 \\ & + 115547145708y_2^2 + 972402y_3^2 + 357656310y_4^2 + 876102111y_5^2 - 985304579y_1y_2 - 242771174y_1y_3 - 45146725893y_1y_4 \\ & - 11456528607y_1y_5 + 29336310y_2y_3 - 3209022460y_2y_4 - 5886970440y_2y_5 - 16975251y_3y_4 - 45573794y_3y_5 + 773340851y_4y_5 \end{aligned}$$

B. Regression Analysis

There are many methods to judge the effect of response surface model, in which the complex correlation coefficient R2 (which is defined in (7)) can be used to represent the linear relationship between the variables.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \tag{7}$$

In the formula, n is the number of samples, y_i the response is true, $\hat{y}_i$ as the response surface fitting value, $\bar{y}_i$ real response mean. 0-1 is the real number, the closer to 1 shows that the better fitting effect, the value of more than 0.9 in order to meet the requirements of the preliminary. According to the response surface model, 20 verification samples are checked. The σ complex correlation coefficient is 0.99932, and the complex correlation coefficient of P_{cr2} is about 0.99194. The response surface model can meet the precision requirement of the response surface.

V. MULTI-OBJECTIVE OPTIMIZATION

The structure design of underwater vehicle is a multi-objective optimization problem:

$$\begin{aligned} \min \quad & f(\mathrm{x}) = [f_1(\mathrm{x}), f_2(\mathrm{x}), \dots f_n(\mathrm{x})]^T \\ s.t. \quad & \mathrm{x} \in \mathrm{X} \\ & g_i(\mathrm{x}) \ge 0,\ \mathrm{i} = 1, 2, \dots \mathrm{p} \\ & \mathrm{h}_j(\mathrm{x}) = 0,\ \mathrm{j} = 1, 2, \dots \mathrm{q} \end{aligned}$$

Among them, $f_i(\mathrm{x})$ is the objective function, $g_i(\mathrm{x})$ and

$h_j(\mathrm{x})$ are constraint conditions, $\mathrm{X}=[f_1(\mathrm{x}), f_2(\mathrm{x}),...f_n(\mathrm{x})]^T$ that n as the design variables.

The design process needs to balance the relationship between the weight of the pressure hull and the maximum internal stress and the ultimate load. The improvement of one goal is often at the expense of other goals. The Pareto optimal solution is the solution of the multi-objective problem which makes the objective to reach the optimal state without compromising other objective conditions. The set of these solutions is called the Pareto optimal solution set. The evolutionary algorithm is a kind of effective method to solve the Pareto optimal solution, which can be used to solve the multi objective optimization problem of Pareto. In this paper, the second generation non dominated sorting genetic algorithm (NSGA-II) is used to treat the maximum stress in the structure as the control condition. The weight of the pressure hull structure is calculated using the volume method.

$$\text{Weight}=7800\pi*(y_1^3+y_1^2y_3+2y_1y_3y_4-4y_1^2y_4+4y_1y_4^2+34y_2y_4y_5-17y_2y_5^2) \tag{8}$$

The number of population was 200, the evolution of algebra was about 100, the cross distribution index was about 10, and the variation distribution index was about 20. The Pareto front of the weight of the casing and the ultimate load of the structure are shown in Fig. 5.

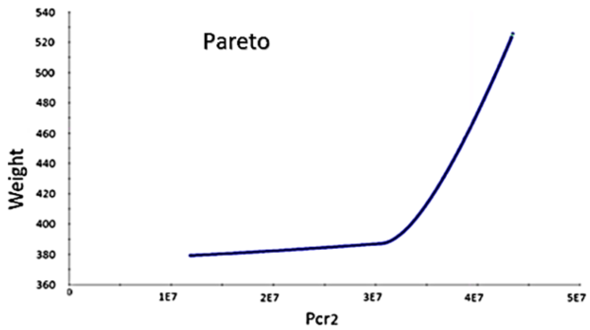

Fig. 5 Pareto frontier of WEIGHT and Pcr2

In this paper, the optimal solution of ISIGHT is given as the multi-objective optimization scheme. The multi-objective optimization scheme is compared with the original scheme, and the data statistics are shown in Table V.

TABLE V
COMPARISON OF MULTI-OBJECTIVE OPTIMIZATION SCHEME OF PRESSURE HULL

Design variable	Initial Scheme	Multi-objective optimization design
Shell thickness (mm)	10	8
Ring rib thickness (mm)	6.00	4
Parallel segment length (m)	5.000	3.400
Shell radius (m)	0.23	0.25
Ring rib height (m)	40	50
Pcr (MPa)	18.270	25.885
Weight (kg)	517.69	376.58

Comparing to the initial scheme, the multi-objective optimization scheme reduced by 27.26% of pressure hull's weight and increased by 41.68% of ultimate load. Ultimate load that the pressure hull can withstand is increased significantly while the weight has been reduced. Obviously, the multi-objective optimization scheme can meet the practical needs of the project better.

VI. CONCLUSION

In this paper, the structural design of AUV pressure hull was studied as an example to optimize the structure of the pressure hull based on response surface method. To determine the optimal variables, we select the test scheme by Opt LHD method. To calculate pressure shell mechanics performance, a parametric driven finite element analysis software ABAQUS was used. The results showed calculation precision in the proposed limits and improved operational efficiency. To avoid human error, accuracy of the response surface method could be verified. The performance index was improved because of the global Pareto optimal solution. The solution set was searched by genetic algorithm, and compared with the original design. The research content has the universal applicability, which provides a reference for the structural optimization design of underwater vehicles.

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