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Study on Comprehensive Optimization Design of UUV Ring-stiffened Cylindrical Shell

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Abstract. The comprehensive optimization design of UUV structure is of great significance to improve the overall performance of the vehicle. In this paper, the mathematical model of the optimization problem of the ring-stiffened cylindrical shell is established under the constraints of the stability and strength, and the multi-objective optimization is carried out with the multi-objective genetic algorithm (MOGA). According to the Pareto solution, the MADM is studied by using the ranking method of TOPSIS, and then the comprehensive ranking of the Pareto optimal solution is obtained. The method of this paper has important engineering guidance for the optimization design of shell structure and the similar engineering practice.

1. Introduction

As an important component of UUV, The ring-stiffened cylindrical shell is used to load the internal function modules and endure pressure at working depth. Now many researches have studied on the strength and stability of underwater vehicle. Song Bao-wei studied the mass optimization of the shell based on the combinatorial optimization[1].The strength and stability of the inner and outer ring rib shells are analyzed and compared in literature [2], and the results show that the strength and stability of the inner rib and the outer rib differ little and the outer rib forms has no obvious advantages[2]. Xiong Chuan-zhi[3] studied on the strength calculation, sealing and anti-corrosion for an AUV pressure-resistant shell. The literature [4] showed the mass optimization of a pressure resistant cabin under the Isight optimization environment. Literature [5] discussed the topological optimization of underwater pressure structures, and proposed a topology optimization method based on image boundary detection. In literature [6], the response surface test optimization design was utilized to optimize the design for the shell of underwater robots. In this paper, Aiming at the structural optimization problem of ring-stiffened cylindrical shell, the multi-objective genetic optimization algorithm is firstly used to solve the problem, then the Pareto optimal solution set is synthesized by TOPSIS method.

2. Structural Stability and Strength Analysis Model of Ring-stiffened Cylinder

2.1. Structural Model of UUV Ring-Stiffened Cylinder

The structure of the ring-stiffened cylinder has good structural stability and space utilization, which is convenient for the layout of the internal instruments and equipment. In order to reduce the mass of the shell, the UUV ring-stiffened cylinder is designed with thin shell plate and rib structure, which can be shown as the Fig.1. The rectangular section design is used in the cylinder structure, and the design variables are shell thickness *t*, shell frame space *m*, rib height *d* and rib width *h*. The design variables of rib number *k*, the length *L* and radius *R* of the cylinder are given.

According to the structure scheme, the shell mass can be obtained as follows:

$$W = 2\pi RLt\rho + 2\pi \cdot (R-t) \cdot hdk\rho \tag{1}$$

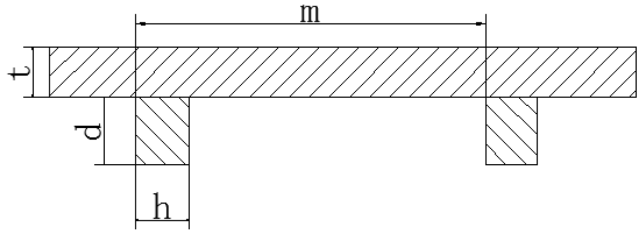

Figure 1. Structural model of UUV ring-stiffened cylindrical shell

2.2. Stability Analysis

Under uniform external pressure, the ring-stiffened cylinder buckling mode includes the overall loss of cabin and the local instability between the ribs, the two critical buckling pressure can be calculated as follows[7]:

(1) Overall stability $P_{cr}{}'$:

$$P_{cr}{}' = \frac{E}{1+\frac{\alpha_1^2}{2(\mathrm{n}^2-1)}}\left[\frac{J(\mathrm{n}^2-1)}{r^3L} + \frac{t\alpha_1^4}{r(\mathrm{n}^2+\alpha_1^2)^2 \times (\mathrm{n}^2-1)}\right] \tag{2}$$

Where *E* means elastic modulus of material, *J* refers to the moment of inertia of the ribs and the connecting shell, *n* refers to wave numbers, *T* is the thickness of the shell, *R* means the shell radius, α_1 is the shell factor parameters which can be calculated by $\pi r/L$.

(2) Local stability $q_{cr}{}'$:

The local buckling of the rib $q_{cr}{}'$ caused by the critical pressure is calculated by:

$$q_{cr}{}' = \frac{E}{n^2+0.5\alpha^2-1}\left[\frac{t\alpha_1^4}{r(n^2+\alpha_1^2)^2} + \frac{t^3(n^2+\alpha^2-1)^2}{12(1-\mu^2)r^3}\right] \tag{3}$$

Where μ denotes material Poisson's ratio. α can be calculated by $\pi r/l$ and l is the length of the shell between ribs. *n* refers to wave numbers. In practical application, it is necessary to revise the theoretical critical pressure Eq. (2) and Eq. (3). The actual local critical instability pressure Q_{cr} and the overall critical instability pressure P_{cr} are calculated as follows:

$$Q_{cr} = q_{cr}' \times \eta_1 \times \eta_2 \tag{4}$$

$$P_{cr} = P_{cr}' \times \eta_1 \times \eta_2 \tag{5}$$

Where η_1 is the correction factor for the geometric nonlinearity of the shell, η_2 is the correction factor considering the physical nonlinearity, which are referred to in Ref. 1.

2.3. Strength Analysis Model

Three strengths need to be calculated for the strength analysis of shell. They are transverse average stress of shell plate at midpoint of span σ_2^0, longitudinal equivalent stress of shell plate at rib σ_1 and the stress on the rib σ_f, and they can be calculated as follows:

(1) Transverse average stress of shell plate at midpoint of span σ_2^0:

$$\sigma_2^0 = -K_2^0 \frac{P_j R}{t} \tag{6}$$

(2) Longitudinal equivalent stress of shell plate at rib σ_1:

$$\sigma_1 = -(0.91 \cdot K_1 - 0.3 \cdot K_f) \frac{P_j R}{t} \tag{7}$$

(3) The stress on the rib σ_f:

$$\sigma_f = -K_f \cdot \frac{P_j R}{t} \tag{8}$$

Where P_j denotes the external pressure on the shell. K_2^0 、 K_1 and K_f are stress coefficients whose calculation can be referred to the literature [7].

3. Mathematical Modeling of Optimization Problems

3.1. Design Variables

According to the structural design parameters of the ring-stiffened cylindrical shell, the design variables of structural optimization problem includes shell thickness *t*, rib spacing *m*, rib height *h* and rib width *n*. Different shell structures can be obtained from the combination of the four variables and the known shell length *T* and radius *R*.

3.2. Constraint Conditions

The structural design parameters including shell thickness *t*, rib spacing *m*, rib height *h* and rib width *n* need to meet certain design range.According to the overall design requirements of UUV, the shell structure design needs to meet the strength and stability constraints of the shell:

$$\sigma_2^0 \le 0.85\sigma_s, \sigma_1 \le \sigma_s, \sigma_f \le 0.55\sigma_s, Q_{cr} \ge P_j, P_{cr} \ge 1.3P_j \tag{9}$$

Where σ_s means yield strength of shell material.

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3.3. Objective Function

The objective of the optimization design of the shell structure is to pursue the optimal synthesis of the lightest shell mass, structural strength and stability, which belongs to a typical multi-objective optimization problem:

$$\min W, \max \left\{ \sigma_2^0, \sigma_1, \sigma_f, q_{cr}, P_{cr} \right\} \quad (10)$$

4. Optimal Solution and Results Analysis

4.1. Optimization Method Selection

MOGA is more efficient in solving multi-objective optimization problems and has been widely used in various fields [8]. Therefore, MOGA is used to realize the structure optimizationin in this paper. A multi-objective problem may have some Pareto optimal solutions, and it needs design personnel to choose one or some solutions as the ‘best’ solutions from the Pareto set. In fact, this problem belongs to MADM which is the ordering problem of a finite decision scheme with multiple attribute indices[9]. The TOPSIS method is an effective multi index evaluation method. By constructing the evaluation problem of positive ideal and negative ideal solution, namely the optimal index of the solution and the worst solution, and close to the positive ideal solution and far away from the negative ideal solution.TOPSIS sort the alternative based on the calculation of the relative closeness of each scheme to the ideal scheme, so as to select the optimal scheme. In this paper, The parameters of MOGA are set as follows: population size is 80, evolution algebra is 100, crossover rate is 0.4 variation probability is 0.02.

4.2. Initial Conditions

The length of cylindrical shell *L* is 1000mm and the outer diameter *R* is 534mm. The working depth water pressure is 2.34Mpa. The material of shell and rib is set as aluminum alloy with density of 2700 kg/m^3, yield strength σ_s of 250MPa, Young modulus of 70GPa and Poisson ratio of 0.3.The range of design variables is shown in Tab.1. *t* value is between 4 and 10, *m* value is between 150 and 250, *d* value is between 15 and 25, *h* value is between 20 and 30.

4.3. Optimization Result Analysis

4.3.1. Pareto Solution Analysis. Fig. 2 shows the relationship between the three stresses and the mass of the structural strength. It can be seen from Fig. 2 that σ_2^0, σ_1 and σ_f decrease with the increase of the shell mass W. Obviously, as the shell structure variable design is more relaxed, the strength requirements can better meet the use requirements, while the cost is the increase of the shell mass. Among them, the range of σ_1 is the largest, σ_2^0 is second, and σ_f is the smallest. This is mainly due to the maximum constraint range of σ_1, the stress σ_2^0 next, and the constraint range of stress σ_f minimum.

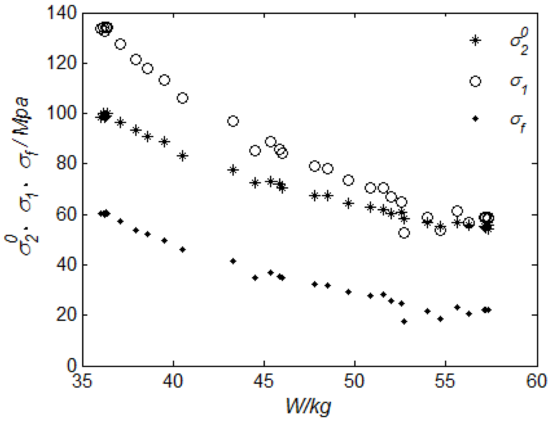

Figure 2. Relationship of mass vs. strength stresses

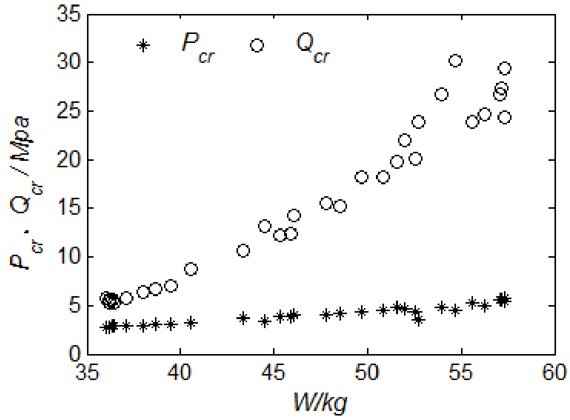

Figure 3. Relationship of mass vs. stability stresses

Fig. 3 shows the relationship between the two instability stresses and the mass. It can be found from Fig.3 that the overall instability stress P_{cr} varies little with the mass, while the local instability stress Q_{cr} varies greatly. The value of P_{cr} varies linearly with the mass, while the value of Q_{cr} varies linearly with the mass when the mass is less than 53kg. In order to further discuss the relationship between these two properties, the scatter diagrams between Q_{cr} and P_{cr} with the three strength stresses are given respectively in Fig.4 and Fig.5, which can be used by designers to balance the two attributes.

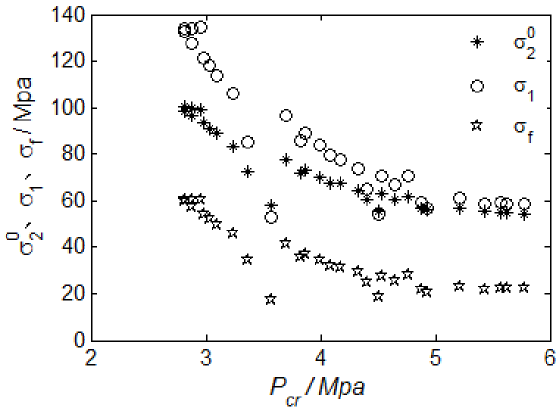

Figure 4. Scatter of overall instability vs. stresses

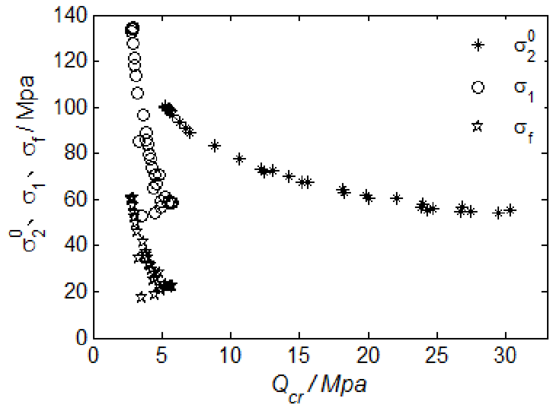

Figure 5. Scatter of local instability vs. Stresses

4.3.2. MADM of Pareto solution. MADM analysis need to determine the weight of index attributes, this paper set the index weights as follows: 0.4 for W; 0.1 for σ_2^0; 0.15 for σ_1; 0.1 for σ_f; 0.15for Q_{cr}; 0.1 for P_{cr}. The detailed calculation procedure of TOPSIS method can be referred to the literature[10]. According to this method, the first 8 feasible schemes for the optimal ordering of Pareto solutions are obtained, as shown in Table 1. The corresponding objective functions and evaluation results are shown in Table 2. According to the sorting result of Table 2, the ninth sample is chosen as the best design scheme.

Table 1. The first eight design samples from Pareto sets

Number	t (mm)	m (mm)	d (mm)	h (mm)	Number	t (mm)	m (mm)	d (mm)	h (mm)
9	5.5	19.3	27.8	132.6	18	5.5	19.9	27.8	141.8
3	5.5	19.9	27.8	135.6	29	5.7	19.6	27.7	141.1
19	5.6	19.4	27.7	136.3	25	5.9	19.7	27.4	141.1
7	5.5	19.6	27.7	140.5	10	6.1	19.6	27.5	141.2

Table 2. MADM results of Pareto sets

Number	W (Kg)	σ_2^0 (Mpa)	σ_1 (Mpa)	σ_f (Mpa)	Q_{cr} (Mpa)	P_{cr} (Mpa)	Comprehensive evaluation	Order
9	36.03	98.44	133.70	60.25	5.71	2.82	0.8641	1
3	36.35	98.90	134.41	60.78	5.54	2.96	0.8640	2
19	36.22	98.64	132.65	59.68	5.58	2.81	0.8608	3
7	36.19	100.10	134.10	60.40	5.28	2.81	0.8602	4
18	36.40	100.00	133.90	60.44	5.25	2.88	0.8597	5
29	37.10	96.63	127.71	57.13	5.76	2.88	0.8500	6
25	37.98	93.22	121.63	53.88	6.32	2.98	0.8360	7
10	38.63	91.07	117.96	51.98	6.71	3.03	0.8221	8

5. Conclusion

In this paper, comprehensive optimization for UUV ring-stiffened cylindrical shells are studied by using MOGA and MADM method. The optimization results show that the MOGA can effectively search the Pareto optimal solution of the design variables of the ring-stiffened cylindrical shell. On the basis of TOPSIS's theory and method, the Pareto solution set is comprehensively evaluated. The optimization method of this paper can provide guidance for the similar engineering problems.

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