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Topology and opening size optimization design of solid floors in an outer tank of the pressure hull

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Abstract: [**Objectives**] In order to simplify the construction process and to reduce the weight of the structure, topology optimization and opening size optimization of solid floors in an outer tank of the pressure hull are conducted. [**Methods**] In the study, Hyperworks/Optistruct is adopted to analyze the strength characteristic of the whole structure. The part of the solid floors 100 mm away from outer tank and pressure hull is defined as design space of the topology optimization. And the elements densities within the defined design space are taken as the design variables. The volume fraction of the design space and the typical stress values of the pressure hull and outer tank are assumed as design constraints while the objective is to minimize the maximum stress on the solid floors. Hyperworks/Optistruct is used to optimize the solid floor in outer pressure tank under full and empty loadings. Then, the size optimization of opening based on the Matlab and ANSYS is conducted. The von Mises and shear stresses of the solid floor are regarded as design constraints, and the weight of the solid floor including the stiffeners on them is treated as objective function to be minimized. A precise optimal scheme of openings is obtained through the above process. [**Results**] The result of topology optimizations shows that holes should be placed on the middle-lower part of the solid floors. The result of opening size optimizations indicates that, compared with the initial scheme, the weight of the optimal solid floor with opening is decreased by 19% with the 38% increase in shear stress and equivalent levels of the other stresses. [**Conclusions**] Both the optimization designs show that openings should be placed on the middle-lower part of the solid floor and their size should be gradually decreased from lower part to middle part of the solid floor.

Key words: outer tank of the pressure hull; topology optimization; opening size optimization

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0 Introduction

The outer tank of the pressure hull should bear the same pressure as the pressure hull underwater. At present, the solid floors in outer tank of the pressure hull with inner longitudinal reinforcement on the outer tank or without reinforcement on the outer tank are usually adopted, but this kind of structure is complicated, heavy and inconvenient for construction [1]. Therefore, it is necessary to study the opening form of solid floor structure in outer tank of the pressure hull to effectively simplify the structural type of solid floor and reduce the structural weight.

Huang et al.[2] optimized the design of solid floor-type pressure tank with inner longitudinal reinforcement on the outer tank. On the basis of the Sys-

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ware platform and meeting the requirements of the current specifications, the main design variables, constraint conditions and objective function for the optimization design of pressure tank were proposed. Through the optimization calculation of specific examples, the optimization design direction of pressure tank was put forward, and improvement suggestions were proposed for the design of lightening holes on the solid floors. Li [3] took shell thickness, frame spacing, model and quantity as design variables, used branch and bound method and sequential quadratic programming method to discuss the relationship among diving depth, geometric parameters and weight of materials and other characteristic quantities, and studied the way to reduce the weight of cylindrical pressure hull for manned submersible. Through the goal programming model, Ding et al. [4] established the goal programming model for the single-objective nonlinear constrained optimization of pressure hull, solved the optimal solution of continuous and discrete mixed variables, and finally obtained the relatively effective solution for the pressure hull with light weight.

Scholars have done a lot of research on optimization, and topology optimization of structures is considered more challenging and promising in engineering applications compared with size optimization and shape optimization [5-6]. Luo et al. [7] conducted topology optimization of the compliant mechanism based on variable density method, compared and studied the solid isotropic material with penalization (SIMP) model and rational approximation of material properties (RAMP) model, which were widely used in engineering. Zegard et al.[8] took the element density in the design area as the design variable and the structural compliance minimization as the objective to conduct topology optimization on a 3D bridge area and obtained a new bridge structure.

Zhang et al. [9] discussed the application of topology optimization and shape optimization in ship structural design. The shape and size optimization was conducted on the bottom grillage, and the structural weight was reduced by 15.82% after optimization. The topology optimization was carried out on the superstructure grillage and a new structural type with more reasonable material distribution was obtained. Li [10] conducted topology optimization on the internal plane bulkhead bracket structure and proposed a new type of outer curved bracket structure. Cheng et al.[11] made a topology optimization analysis on the typical ship bracket structure of nodes and proposed a new type of bracket structure. Compared with the traditional triangular bracket, the new bracket structure effectively reduced the stress concentration of nodes. Gao et al.[12] conducted shape and topology optimization on the corner structure of rectangular pressure tank and proposed the optimal curved corner shape when the stress concentration of the structure was minimized.

At present, topology optimization has been widely used in automobile, aerospace engineering and other fields, and there are also a few applications in ship industry, but there are few cases about the topology optimization design of solid plates in pressure tank. In this paper, topology optimization of opening is conducted on solid floors in outer tank of the pressure hull based on optimization software Hyperworks/Optistruct, trying to answer the problem of how to open holes correctly on solid floors by means of topology optimization. Through engineering treatment and scheme comparison, the stress at the same level as the no-opening scheme is obtained. However, the structural weight in the scheme of opening structure of solid floors is decreased. Then, based on Matlab and ANSYS joint simulation, opening size optimization is carried out to obtain a refined scheme.

1 Stress analysis of outer tank of the pressure hull

1.1 Overall model and load

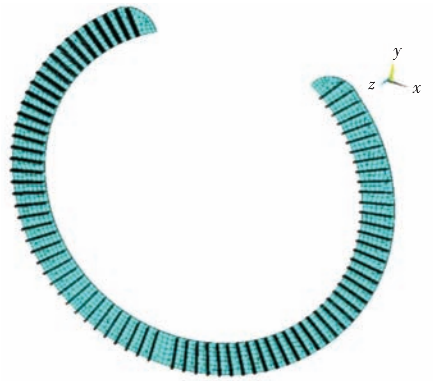
The outer tank of the pressure hull with solid floors reinforced by inner longitudinals is selected as the research object, as shown in Fig. 1. The global coordinate system of the finite element model of the whole structure is cylindrical coordinate system. The radial direction of the cylindrical pressure hull is the X-axis; the circumferential direction is the Y-axis; and the axial direction is the Z-axis. In the finite element model of the whole structure, beam element Beam188 is used to simulate the longitudinal and

Fig.1 The whole structure diagram of outer tank of the pressure hull

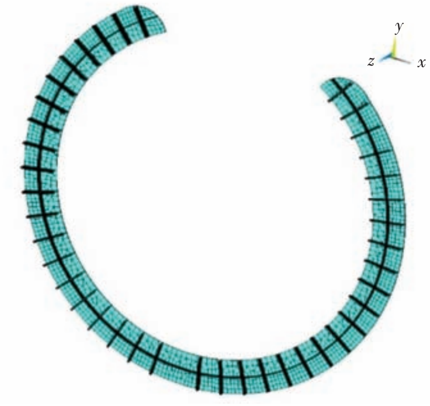
transverse bulkhead stiffeners of pressure tank, ring ribs on solid floors and radial reinforcing ribs. However, other structures are simulated by shell element Shell181. The grid size is 100 mm. The whole model is divided into 76 527 shell elements and 8 860 beam elements.

The diameter-length ratio of the pressure tank is 1.714; the shell thickness is divided into 16, 18 and 32 mm; the frame spacing is l=0.6 m; and the longitudinals of the outer tank adopt flat-bulb steel 18a. The pressure hull extends 5-frame spacing along the external tank to the positive direction of Z-axis (fore end) and 12-frame spacing to the negative direction of Z-axis (aft end). The ratio of pressure hull diameter to tank diameter is 0.833, and the shell thickness is 24 mm. The thickness of solid floors at both ends and the angle of radial reinforcing ribs are 14 mm and 3.6° respectively, while the thickness of inner solid floor and the angle of radial reinforcing ribs are 12 mm and 7.2° respectively. The dimension of ring ribs of solid floors is 16 mm × 80 mm, and the radial reinforcing ribs adopt flat-bulb steel 12. The dimension of the frames in the pressure tank is $\frac{14\times164}{26\times80}$, and the dimension of the ring ribs in the non-pressure tank is $\frac{12\times160}{20\times54}$. The thickness of bottom center line girder is 18 mm. Transverse bulkheads are set at 2-frame spacing in the positive direction of Z-axis (fore end) and 11-frame spacing in the negative direction of Z-axis (aft end) of the external tank respectively. Their thickness is 80 mm and there are cross T-shaped materials with the dimension of $\frac{12\times160}{20\times54}$. The elastic modulus of structural materials is E=196 GPa; the Poisson's ratio is μ=0.3; and the material density is ρ=7 800 kg/m^3. The structure of end sealing plate and inner solid floor is shown in Fig. 2.

Under the conditions of full load and empty load of the tank, the same constraint is applied to constrain the translational and rotational degrees of freedom in the three directions of X, Y and Z at the right end of the cabin model. At the left end of the cabin, the translational degree of freedom (DOF) in the X and Y directions and the rotational DOF in the X, Y and Z directions are constrained. Under full load condition, pressure of 5 MPa is applied on the whole pressure hull. Under the empty load condition of the tank, pressure of 5 MPa is applied on the outer surface of the cabin, the outer tank and the sealing plates at both ends. Under both conditions, the end water pressure is converted into nodal force, which is applied at the left end of the cabin along axial direction.



(a) End sealing plate

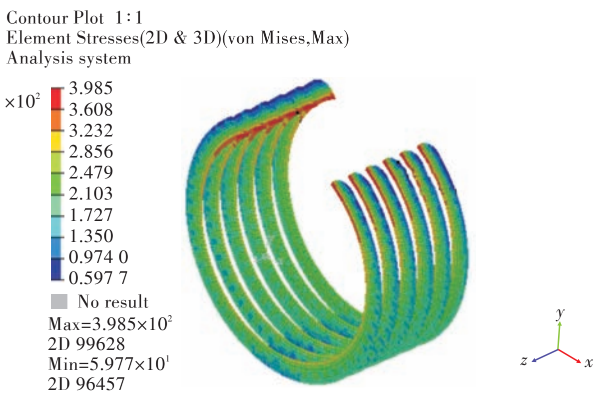


(b) Inner solid floor

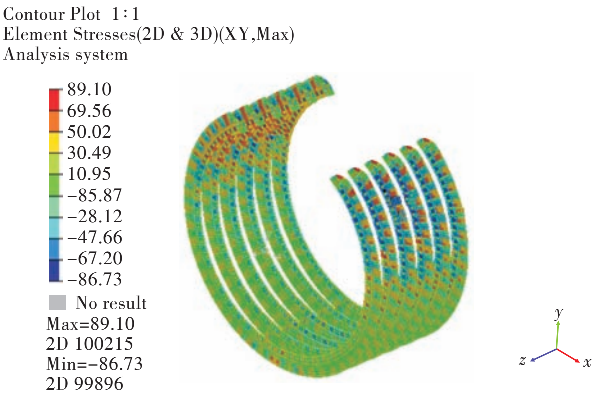
Fig.2 The structure diagram of solid floors in an outer tank of the pressure hull

1.2 Analysis of model stress calculation results

The finite element model is imported into the optimization software Hyperworks/Optistruct for strength calculation. The contour of von Mises stress and shear stress of solid floors under the conditions of full load and empty load is shown in Fig. 3 and Fig. 4 respectively. The stress calculation results of typical areas are shown in Table 1.

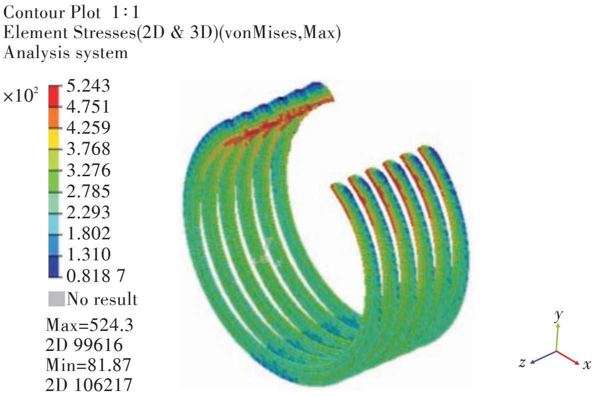


(a) The von Mises stress of solid floors (398 MPa)

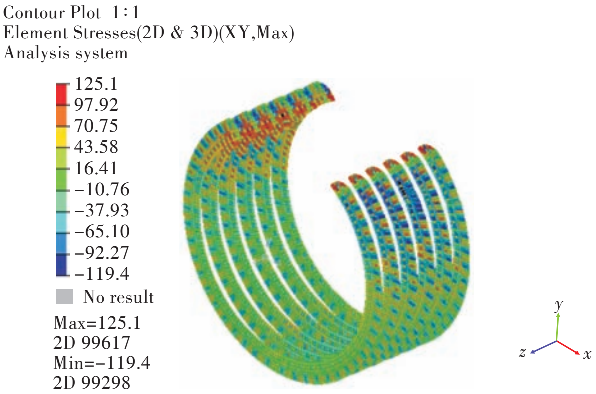


(b) Shear stress of solid floors (89 MPa)

Fig.3 The von Misses stress and shear stress contours of the solid floors under full loadings



(a) Mises stress of solid floors (524 MPa)



(b) Shear stress of solid floors (125 MPa)

Fig.4 The von Mises stress and shear stress contours of the solid floors under empty loadings

Table 1 The stress results of interested areas

Load type	Max. Mises stress of solid floors /MPa	Max. Mises shear stress of solid floors /MPa	Max. Mises stress of outer tank /MPa	Max. Mises stress of pressure hull /MPa
Full load condition	398	89	354	543
Empty load condition	524	125	527	798

Fig. 3 and Fig. 4 show that the maximum Mises stress and shear stress of solid plates appear at the connection between the top of solid plates and the pressure hull. As can be seen from Table 1, under full load and empty load conditions, empty load condition is more dangerous than full load condition.

2 Topology optimization of opening of solid floors in outer tank of the pressure hull

2.1 Mathematical model of topology optimization

The topology optimization design of solid floors is aimed at providing a new technical method for the determination of opening area and shape of solid floors. According to the structural characteristics of solid floors in the outer tank of the pressure hull, and considering the consistency of the solid floor structure and the similarity of the force conditions (except the solid floor at both ends), topology optimization is carried out on the six inner solid floors, and the model is set to repeat during the optimization process.

In the optimization calculation, both full load and empty load conditions are considered at the same time, and the design space is the inner space of solid floors about 100 mm away from the outer tank and the pressure hull, as shown in Fig. 5. The design variable is the element density in the design space of solid floors (element density is between 0 and 1). The mathematical model of topology optimization is shown in Table 2.

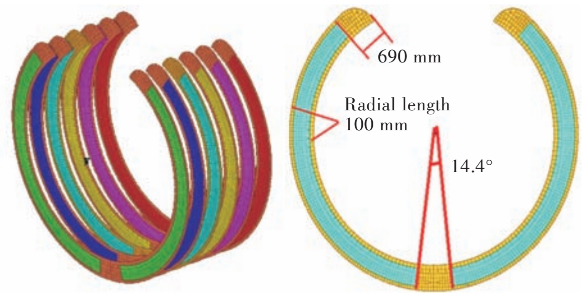


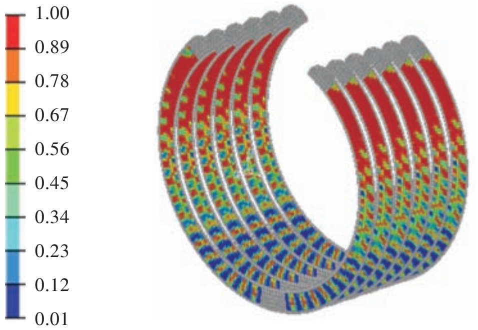
Fig.5 Design space diagram of the topology optimization

Table 2 Mathematical model of the topology optimization

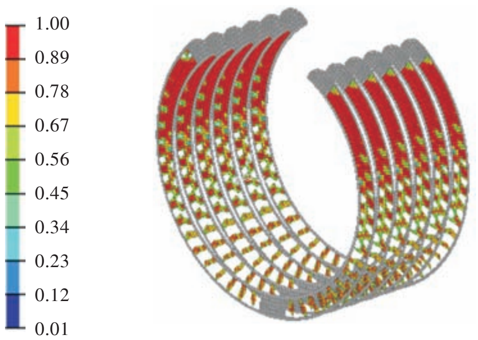
Design variable	Constraint condition	Objective function
Element density in design space of solid floors	Mises stress in interested area of outer tank is not greater than 390 MPa (full load condition) and 590 MPa (empty load condition) Mises stress of interested area in pressure hull is not greater than 543 MPa (full load condition) and 800 MPa (empty load condition) Volume fraction of design area is not greater than 60%	Minimization of max. Mises stress in solid floors

2.2 Topology optimization results

The above mathematical model is solved, and the calculation is stopped when the optimization scheme is optimized for the 33-step iteration. The element density diagram of solid floor structure under convergence is shown in Fig. 6. The red area represents element density of 1, and the blue area represents element density of 0.



(a) Design variables remain at 0–1.0



(b) Design variables remain at 0.5–1.0

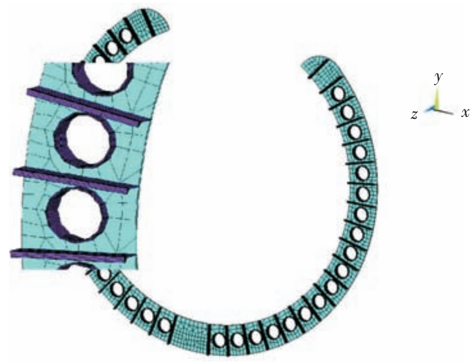
Fig.6 Element density contours of design space

Topology optimization converges in the last step, and the residual volume fraction of the design area is 60%, which satisfies the constraint conditions. Fig. 6 shows that the lightening holes of solid floors in the outer tank of the pressure hull should be concentrated in the middle-lower part, and the opening area from bottom to top should be gradually reduced.

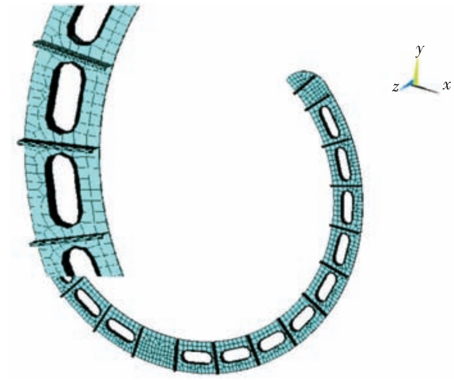
3 Engineering treatment of optimization results and scheme comparison

3.1 Engineering treatment schemes of optimization results

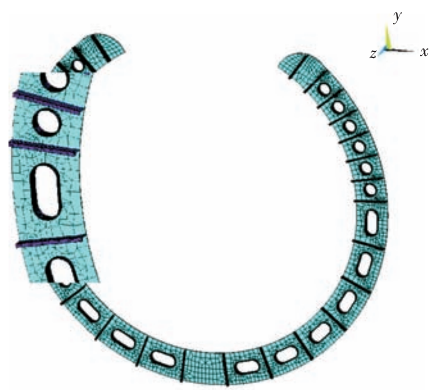
According to the optimization results obtained in Section 2.2, engineering treatment is carried out on the solid floor structure, and ANSYS is used for verification and comparison. The diagrams of opening on the solid floors in each scheme are shown in Fig. 7



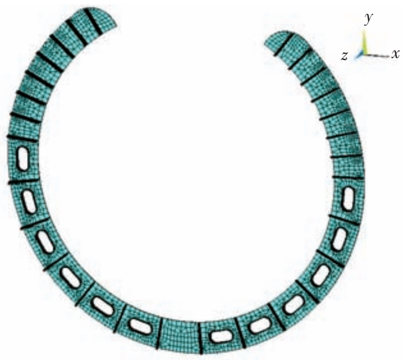
(a) Scheme 1: remove ring ribs of solid floors, open 36 round holes with a diameter of 300 mm, and add fences of 10 mm× 100 mm to the round holes



(b) Scheme 2: remove ring ribs of solid floors, open 18 obround holes of 240 mm× 415 mm, and add fences of 10 mm× 100 mm to the round holes



(c) Scheme 3: remove ring ribs of solid floors, open 12 obround holes of 240 mm× 250 mm and 12 round holes with a diameter of 240 mm, and add fences of 10 mm× 100 mm to the obround holes and round holes



(d) Scheme 4: remove ring ribs of solid floors, open 12 obround holes of 240 mm× 250 mm, and add fences of 10 mm× 100 mm to the obround holes

Fig.7 Engineering schemes of opening form on the solid floors (the length of the obround hole is the distance between the centers of the two sides).

3.2 Comparison of structural strength schemes

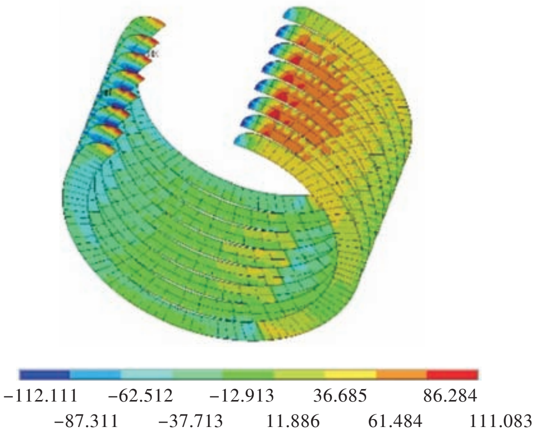
According to the comparison of the calculation results of the initial scheme of outer tank of the pressure hull under full and empty load conditions shown in Table 1, the empty load condition is more dangerous than the full load condition. Therefore, the structural strength of several schemes is only compared under the empty load condition. Stress calculations are performed for the engineering schemes 1 to 4 respectively. The results of the initial scheme and the four schemes of opening form on solid floors under the empty load condition are shown in Table 3. The shear stress of solid floors in the four schemes is shown in Fig. 8. The overall weight of the structure is denoted as M; the weight of the inner solid floor and the reinforcement is M_{solid}; the longitudinal stress on the inner surface of outer tank at the root of solid floors is $\sigma_{\text{tank inner longitudinal}}$; the circumferential stress on the inner surface of outer tank at the root of mid-span longitudinals of adjacent solid floors is $\sigma_{\text{tank inner circumferential}}$; the total stress on the free flange of tank longitudinals at the root of solid floors is $\sigma_{\text{tank longitudinal}}$; the shear stress on the end webs of tank longitudinals is $\sigma_{\text{tank longitudinal shear}}$; the longitudinal stress on the outer surface of pressure hull at the root of solid floors is $\sigma_{\text{hull outer longitudinal}}$; the longitudinal stress on the inner surface of mid-span pressure hull of adjacent solid floors is $\sigma_{\text{hull inner longitudinal}}$; the frame stress is σ_{frame}; the total stress of solid floors is $\sigma_{\text{solid total}}$; the circumferential stress of solid floors is $\sigma_{\text{solid circumferential}}$; and the shear stress of solid floors is $\tau_{\text{solid shear}}$ (the absolute value of the shear stress is shown in the table). The rate of change as shown in the Table 3 is the change of schemes 1–4 relative to the initial scheme.

Table 3 and Fig. 8 show that the existence of ring ribs on the solid floors has little effect on the stress of interested areas. In addition, compared with the initial scheme, except that the shear stress on solid floors increases a lot, the stress results of other interested areas in the four schemes change little.

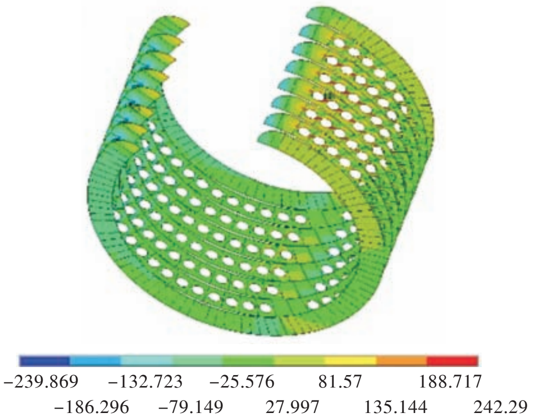
By comparing the shear stress contours of solid floors in scheme 1 and scheme 2, we can see that the maximum shear stress on solid floors appears at the upper opening, which is significantly increased compared with that in the initial scheme, indicating that openings should not be placed on the upper part of solid floors. Table 3 shows that in the engineering treatment scheme 3 obtained according to the topology optimization results in Section 2.2, obround holes are opened on the lower part of solid floors and round holes are opened on the upper part. Scheme 4 is obtained by removing the upper holes of scheme 3. Compared with the initial scheme, the stress level of interested areas remains unchanged. The relatively large change in stress is the shear stress on solid floors, which increases by 57% and 49% respectively in scheme 3 and scheme 4. The maximum shear stress appears at the upper holes, indicating that the opening on the upper part of solid floors will increase the shear stress of solid floors. The upper holes should be further reduced, or as in scheme 4, no hole is made on the upper part of solid floors. The following section will determine the opening size on solid floors within the allowable stress range by the size optimization.

Table 3 Comparison of results among different opening forms under empty loadings

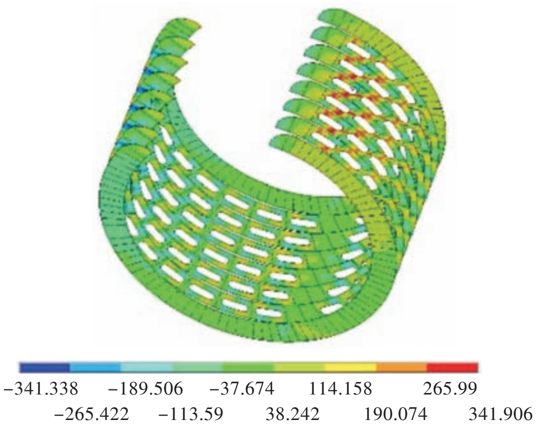
Parameter	Eigenvalue of initial scheme	Scheme 1		Scheme 2		Scheme 3		Scheme 4	
		Eigenvalue	Change rate /%	Eigenvalue	Change rate /%	Eigenvalue	Change rate/%	Eigenvalue	Change rate /%
M/t	132.12	131.26	−1	130.32	−1	130.78	−1	130.66	−1
M_{solid}/t	8.2	7.34	−10	6.4	−22	6.86	−16	6.74	−18
$\sigma_{\text{tank inner longitudinal}}$/MPa	−353	−342	−3	−345	−2	−343	−3	−344	−3
$\sigma_{\text{tank inner circumferential}}$/MPa	−456	−468	3	−483	6	−456	0	−457	0
$\sigma_{\text{tank longitudinal}}$/MPa	388	412	6	431	11	410	6	410	6
$\sigma_{\text{tank longitudinal shear}}$/MPa	35	35	0	32	−9	35	0	35	0
$\sigma_{\text{hull outer longitudinal}}$/MPa	−1 051	−1 063	1	−1 075	2	−1 063	1	−1 062	1
$\sigma_{\text{hull inner longitudinal}}$/MPa	−824	−831	1	−829	1	−830	1	−827	0
σ_{frame}/MPa	−495	−501	1	−508	3	−496	0	−494	0
$\sigma_{\text{solid total}}$/MPa	517	529	2	810	57	519	0	525	2
$\sigma_{\text{solid circumferential}}$/MPa	−555	−573	3	−794	43	−565	2	−568	2
$\tau_{\text{solid shear}}$/MPa	112	242	116	342	205	176	57	167	49



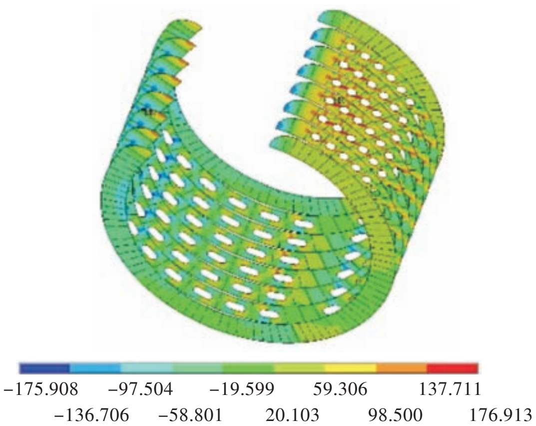
(a) Initial scheme (112 MPa)



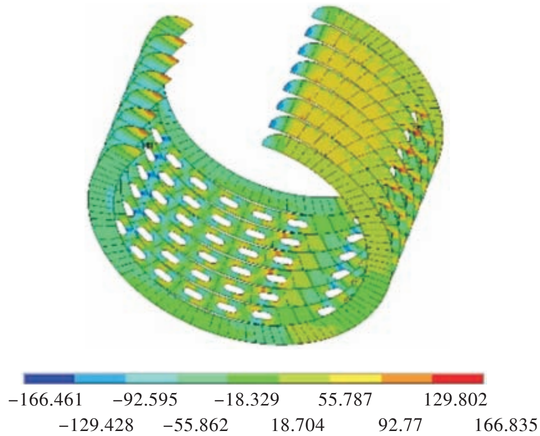
(b) Scheme 1 (242 MPa)



(c) Scheme 2 (342 MPa)



(d) Scheme 3 (176 MPa)



(e) Scheme 4 (167 MPa)

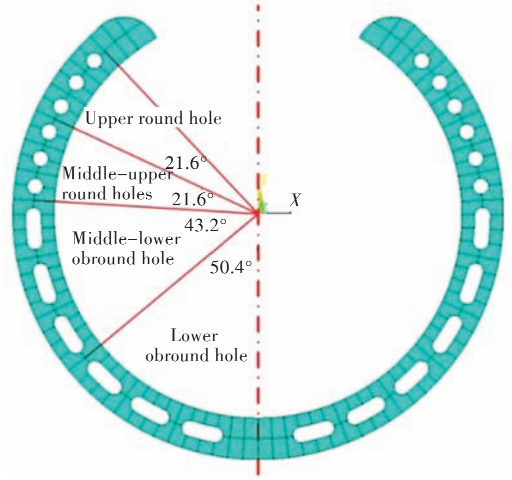
Fig.8 Shear stress contours of solid floors under empty loadings

4 Opening size optimization of solid floors in outer tank of the pressure hull

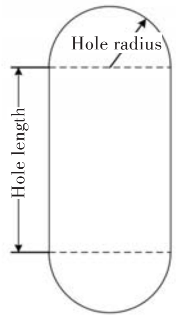
Fine design is further made for the opening of inner solid floor in order to obtain the optimal opening method. Since the empty load condition is more dangerous than the full load condition, the opening size optimization design only needs to be carried out for the empty load condition. First, ANSYS parametric design language (APDL) is used to conduct parametric modeling of outer tank of the pressure hull structure. Then the objective function, constraint conditions and design variables are determined, and the corresponding mathematical model of optimization design is established. The master control program of optimization is written based on Matlab platform, and the finite element analysis program ANSYS is called through the master control program. Data transfer is conducted between the two programs to optimize the size of solid floors of the outer tank of the pressure hull structure, and the optimization results are tested and analyzed.

4.1 Mathematical model of optimization

In the optimization calculation, the objective function is to minimize the structural weight under the empty load condition. Considering that the shear stress on the inner solid floor in Section 3.2 increases a lot, the constraint condition is that the von Mises stress on the inner solid floor does not exceed 525 MPa and the shear stress does not exceed 160 MPa. The design variables are various opening sizes, as shown in Fig. 9, and the value space is shown in Table 4. Genetic algorithm is used for the optimization solution.



(a) Grouping of opening schemes



(b) Diagram of obround hole

Fig.9 Diagram of design variables

Table 4 The value space of design variables

Design variable	Description	Value space/mm
x_1	Radius of lower obround holes	{50, 100, 150, 200}
x_2	Length of lower obround holes	{150, 200, 250, 300, 350}
x_3	Radius of middle-lower obround holes	{50, 100, 150, 200}
x_4	Length of middle-lower obround holes	{100, 150, 200, 250, 300}
x_5	Radius of middle-upper round holes	{0, 10, 20, 30, 40}
x_6	Radius of upper round holes	{0, 10, 20, 30, 40}

4.2 Size optimization results and analysis

The convergence of the optimization model is checked, and the results show that the global optimal solution can be obtained by setting the population size of 300 × 15 (namely that the generation number of optimization iteration is 15, and each generation contains 300 individuals) when the von Mises stress and shear stress on the inner solid floor are constrained. In this paper, when the population size is 300 × 15, a total of 1 038 schemes are generated in the whole optimization calculation process. The iteration number of the whole optimization is about 1 038, accounting for 10.37% of the 10 000 full-combination schemes. The global optimal solution can be quickly searched with a small sample size.

Under the empty load condition, the constraint condition in the optimization model is that the von Mises stress on the inner solid floor does not exceed 525 MPa and the shear stress does not exceed 160 MPa. The optimization goal is to minimize the structural weight, and single-objective optimization design is conducted. In the optimal scheme, the radius and length of the lower holes are 150 mm × 250 mm; the radius and length of the middle-lower holes are 150 mm × 150 mm; the radius of the middle-upper holes is 10 mm; and the radius of the upper holes is 10 mm. The optimized size of the radius of middle-upper and upper holes is very small, indicating that under the constraint of shear stress, the opening should not be placed on the middle-upper part of solid floors. The stress results comparison of interested areas in the initial and the optimization schemes is shown in Table 5.

Table 5 Stress results of interested areas of initial and optimization schemes

Parameter	Eigenvalue of initial scheme	Optimization scheme	
		Eigenvalue	Change rate/%
M/t	132.12	130.47	−1
M_{solid}/t	8.2	6.66	−19
$\sigma_{tank\ inner\ longitudinal}$/MPa	−353	−344	−3
$\sigma_{tank\ inner\ circumferential}$/MPa	−456	−463	2
$\sigma_{tank\ longitudinal}$/MPa	388	420	8
$\sigma_{tank\ longitudinal\ shear}$/MPa	35	35	0
$\sigma_{hull\ outer\ longitudinal}$/MPa	−1 051	−1 063	1
$\sigma_{hull\ inner\ longitudinal}$/MPa	−824	−827	0
σ_{frame}/MPa	−495	−494	0
$\sigma_{solid\ total}$/MPa	517	520	1
$\sigma_{solid\ circumferential}$/MPa	−555	−568	2
$\tau_{solid\ shear}$/MPa	112	155	38

It can be seen from the opening size optimization results that the openings on the inner solid floor gradually decrease from the bottom to the top, which is consistent with the topology optimization results in Section 2.2.

Table 5 shows that compared with the initial scheme, the shear stress on solid floors increases by 38% in the optimization scheme, but it is still within the constraint range. The stress of other interested areas is basically consistent with that in the initial scheme, and the weight of the inner solid floor and the reinforcement is reduced by 19%, achieving a good weight reduction effect.

5 Conclusions

In this paper, topology optimization and size optimization are respectively carried out for the opening of solid floors in the outer tank of the pressure hull. Through the engineering treatment of the optimization results and the verification and analysis of the optimization schemes, suggestions for the design of opening structure of solid floors are finally provided, and the following conclusions are drawn:

1) For the outer tank of the pressure hull, the ring ribs on the solid floors have little effect on the stress of interested areas and can be removed.

2) The topology optimization design method for solid floors in outer tank of the pressure hull is proposed. The results of topology optimization design provide useful references for the opening area and opening form of solid floors. The topology optimization results show that the opening on solid floors in the outer tank of the pressure hull should be concentrated in the middle-lower part. In the engineering treatment, according to the results of scheme 1 and scheme 2, the maximum shear stress appears at the upper opening, which is significantly increased compared with that in the initial scheme. Therefore, in order to keep the shear stress on the solid floors basically unchanged, the openings should not be placed on the upper part of solid floors, which is consistent with the topology optimization results.

3) The opening size optimization method for solid floors in outer tank of the pressure hull is proposed, which can further refine and determine the opening size. The size optimization results show that the opening area of solid floors in the outer tank of the pressure hull should gradually decrease from bottom to top, and the openings should not be placed on the upper part. Compared with the initial scheme, the shear stress on solid floors increases by 38% in the optimization scheme, but it is still within the constraint range. The stress of other interested areas is basically consistent with that in the initial scheme, and the weight of the inner solid floor and the reinforcement is reduced by 19%, achieving a good weight reduction effect.

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考虑作动器输出约束的分散中间质量混合隔振系统建模分析

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摘　要:[**目的**]研究舰船主动隔振系统的能量波动特性。[**方法**]首先,建立一种浮筏混合隔振系统广义数理模型,包含有多向复合扰动振源、分布参数主/被动一体式隔振器、分散中间质量及弹性安装基础,并从声振能传递与控制角度揭示系统的耦合振动机理。然后,结合工程中隔振系统的应用,设置等中间质量的浮筏隔振系统作为参照组,研究隔振器内共振、中间结构波动效应、中间质量与机器质量比以及不同作动器布置方案对系统能量传递的影响。[**结果**]分析结果表明:相比于传统的浮筏隔振系统,尤其是在中、高频共振区,分散中间质量隔振系统对于振动能量的隔离效果有明显的提高;对作动器施加约束降低了未施加约束时的理论预测误差。[**结论**]此类混合隔振系统在整个频段内具有良好的隔振效果,隔离性能超过传统隔振系统15 dB以上,且考虑作动器输出约束后更符合工程实际。

关键词: 多维隔振; 分散中间质量; 波动效应; 振动能量; 输出约束

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外置式耐压液舱实肋板拓扑和开孔尺寸优化

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摘　要:[**目的**]为了简化建造工艺和减轻液舱结构重量,对外置式耐压液舱实肋板结构进行拓扑优化和开孔尺寸优化设计。[**方法**]首先,利用Hyperworks/Optistruct对外置式耐压液舱整体模型进行结构应力分析。然后,在拓扑优化中,除与液舱壳板和耐压船体壳板相连的约100 mm长条状范围外,以实肋板其他范围内的单元密度为设计变量;以与实肋板相连的液舱壳板和船体壳板上结构的典型应力及实肋板体积分数为约束,以实肋板上最大Mises应力最小化为目标,针对满载和空舱两种工况,利用商用软件Hyperworks/Optistruct对实肋板结构进行拓扑优化。最后,基于Matlab和ANSYS联合优化,以实肋板上von Mises应力和剪应力为约束,以相应结构重量极小化为目标,对实肋板开孔进行尺寸优化,从而得到精细化开孔方案。[**结果**]拓扑优化结果表明,外置式耐压液舱实肋板开减轻孔应集中在中、下部。开孔尺寸优化结果表明,相比初始方案,实肋板剪应力增加38%,其他关注区域应力相当时,内部实肋板上结构重量可降低19%。[**结论**]两类优化设计均表明,外置式耐压液舱实肋板开减轻孔应集中在中下部,且从下到上开孔面积应逐渐减小。

关键词: 外置式耐压液舱; 拓扑优化; 开孔尺寸优化