DOI: 10.3969/j.issn.1673-3185.2017.06.012 **http:** // english.ship-research.com

Translated from: CHEN Y K, YU E E, LUO W, et al. Optimum design of internal structure of rectangular cabin under internal pressure[J]. Chinese Journal of Ship Research, 2017, 12(6): 81-85.

Optimal design of internal structure of rectangular cabin under internal pressure

CHEN Yangke[1,2], *YU Enen*[1], *LUO Wei*[3], *WANG Hongxu*[3], *CHENG Yuansheng*[1]

1 School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

2 Wuhan Military Representative Department, Naval Armament Department of PLAN, Wuhan 430064, China

3 China Ship Development and Design Center, Wuhan 430064, China

Abstract: [Objectives] In order to efficiently reduce the bending stress of a grillage in a rectangular cabin under internal pressure, mathematical models for the optimization of the vertical positions of platforms and size and layout of pillars are proposed respectively. **[Methods]** The vertical positions of the two internal platforms are taken as the design variables, the maximum bending stress of the transverse and longitudinal bulkhead structures is minimized, and the optimal positions of the internal platforms are obtained via a genetic algorithm. The optimization results show that the best positioning of platforms is close to the vertical uniform distribution. A stepwise optimal pillar design method is proposed. First, the maximum bending stress of the top deck structure is minimized by taking the positions of pillars with the same stiffness as the design variables. Through the repeated use of the model, optimal layout schemes under different numbers of pillars can be obtained in succession. The number and layout of the pillars are then selected according to the stress constraints. To further reduce the maximum bending stress of the top deck structure under a given number and layout of pillars, a mathematical model for the optimal variable stiffness of pillars is proposed. In this study, sectional dimension of pillar is treated as a design variable, the weight of the pillars in the previous round of optimization design is treated as the constraint, and the maximum bending stress of the top deck structure is minimized. **[Results]** The optimization results show that the pillars in the central zone are larger than those in other regions. By using the proposed optimal design models, the maximum bending stress of the transverse and longitudinal bulkheads and top deck is reduced by 28.3%, 25.7% and 13.9% respectively. **[Conclusions]** The proposed method can provide reference points for comparable structural design.

Key words: rectangular cabin under internal pressure; optimal design; internal platform; pillar layout

CLC number: U663.8

0 Introduction

As for the optimal structural design of ships, classical methods for optimal design can hardly adapt to increasing design requirements, while heuristic methods for optimal design have shown a feature of high efficiency[1]. Sekulski[2] adopted the genetic algorithm to optimally design the structure of a catamaran with 37 variables, and the results verified the effectiveness of the method. Klanac et al.[3] also used the genetic algorithm for multi-objective optimal design of ship structures.

Cheng et al.[4-5] optimized the layout and dimensions of ship docking blocks through stepwise optimization. Yang et al.[6] proposed an optimal-design model and a code method for the layout of supports in pipeline system, by referring to standards and other constraints. Cui et al.[7] conducted topology optimization of midship sections and knee plates of container ships through knowledge-engineering-based and

Received: 2017-06-06

Author(s): CHEN Yangke, male, born in 1982, master, engineer. Research interest: ship structure. E-mail: cyk881@163.com

YU Enen, male, born in 1993, master candidate. Research interest: structural analysis and optimal design. E-mail: yuenen@hust.edu.cn

CHENG Yuansheng (Corresponding author), male, born in 1962, Ph.D., professor, doctoral supervisor. Research interest: ship structure analysis and lightweight design, and ship impact dynamics and protection design. E-mail: yscheng@hust.edu.cn

level-set-based methods. Sekulski[8-9] carried out single-objective and multi-objective optimization regarding topological layout of grillages, by adopting the genetic algorithm. Qian et al.[10] proposed a sectionalized dynamic-relaxation collaborative-optimization algorithm by combining the collaborative-optimization algorithm with the hybrid-optimization algorithm as well as the dynamic-relaxation method, and applied the new algorithm to multi-objective structural optimization of marine engine room. Gao et al.[11] respectively put forward mathematic models for shape and topology optimization of corner structures of rectangular cabins under internal pressure, and the optimized corner structures reduced the stress concentration effectively. The stepwise optimization, the combination optimization of pillars, and the genetic algorithm were simultaneously involved in the research of this paper. At present, no research is conducted on pillar structures of ships, and no comprehensive research and analysis are available for the above methods and problems.

This paper aims to propose mathematic models for position optimization of internal platforms and layout optimization of pillars, based on cabin structures under internal pressure, so as to reduce the bending stress of cabin grillages by using the structures of internal platforms and pillars in the most efficient manner.

1 Finite Element (FE) model of a rectangular cabin under internal pressure

1.1 FE analysis of the whole structure

A three-compartment structure of a ship was analyzed in this paper, and the typical characteristic of the structure was that the middle cabin was under a uniform load of 0.8 MPa and was completely stiffened externally. The three-compartment structure had a total length of 19.5 m, a width of 16.5 m, and a molded depth of 12 m, in which the investigated cabin under internal pressure had a length of 12 m, a width of 9 m, and a height of 9 m; the ship bottom was a double-bottom structure, with a height of 1.5 m; the rest were single-layer grillages, and the boards of various grillages had a thickness of 35 mm; girders were arranged with a separation distance of 750 mm; web plates for girders had a height of 750 mm and a thickness of 30 mm; face plates were 250 mm× 35 mm in size. There were two platforms installed at different levels inside the cabin, on which several pillars were arranged. Such pillars ran through the platforms to connect the top deck with the double bottom. The structural materials had the elasticity modulus of E = 210 GPa, the Poisson's ratio of μ = 0.3, and the density of ρ = 7 800 kg/m^3.

As this paper focused on the local strength of the middle cabin of the three-compartment structure under internal pressure, the superposition of the local bending stress and the total longitudinal bending stress was not taken into account temporarily during the structural analysis. The global coordinate system of the FE model was a rectangular coordinate system, with the direction along the ship length towards the ship bow, the leftward direction along the ship width, and the upward direction along the molded depth as positive directions of various axes. The origin of coordinates was located at the intersection point of the rear transverse bulkhead, the starboard longitudinal bulkhead, and the bottom shell plating of the cabin. Cabin panels and web plates of girders were simulated with shell elements of Shell 181, while face plates of girders were simulated with beam elements of Beam 188. The mesh size for the overall model was set to 400 mm. Fig. 1 shows half of the FE model of the whole structure.

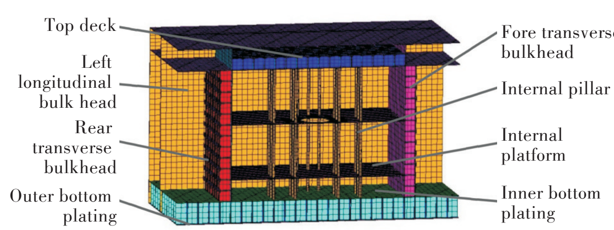


Fig.1 Diagram of FE model of half of rectangular pressure cabin

As the whole model was self-balanced under stress, only one node on the boundary was chosen to constrain all its degrees of freedom, so as to restrict rigid displacement of the model and serve as the boundary constraint.

1.2 Simplified calculation model

For reducing the time required by optimization calculation, and meanwhile, with the consideration that the position optimization of internal platforms mainly aimed to reduce the bending stress of both transverse and longitudinal bulkheads, during the relevant optimization, only transverse and longitudinal bulkheads of the cabin were selected for research, and then, simply support and clamped support constraints were respectively imposed on joints between transverse and longitudinal bulkheads and the top deck as well as the inner bottom. By comparing with results of stress calculation of the same structure in the overall model, it was shown that the boundary constraint under which bending stress at the mid-span of a grillage had a small relative error was a simple-support constraint. Fig. 2 shows the simplified FE model.

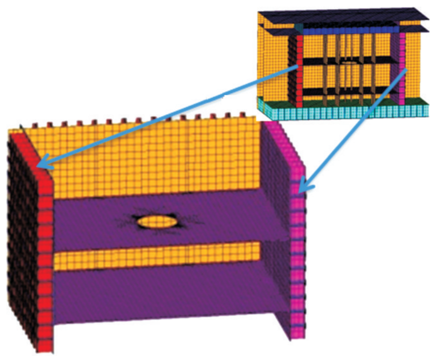


Fig.2 Simplified FE model for platform optimization (starboard not shown)

During the optimal design of internal pillars, considering that arrangement of pillars mainly influences stress of the top deck and the double bottom, only the cabin structure under internal pressure was analyzed, with all-degree-of-freedom constraints being imposed on a selected node. Fig. 3 shows the simplified FE model.

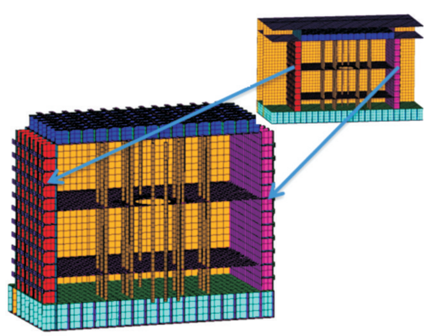


Fig.3 Simplified FE model for pillar optimization (starboard not shown)

2 Position optimization of internal platforms

Two platforms were arranged at different levels inside the cabin, and internal platforms can significantly reinforce the transverse and longitudinal bulkheads. Without increasing the number of platforms or changing their structural dimensions, how to reasonably determine vertical positions of such platforms to minimize the bending stress of both transverse and longitudinal bulkheads is the problem to be solved in the optimal design of platform positions.

2.1 Mathematic model for optimization of platform positions

The mathematic model for optimization of platform positions is given as follows:

$$\begin{aligned} \text{Find:} \quad & \boldsymbol{X}=[x_1, x_2]^{\mathrm{T}} \\ \text{s.t.} \quad & x_{i,\min} \leqslant x_i \leqslant x_{i,\max}\ ; \quad i=1,2 \\ & |x_1 - x_2| \geqslant C \\ \min: \quad & \max(\sigma_{\mathrm{M}}(\boldsymbol{X})) \end{aligned} \tag{1}$$

where x_1 and x_2 refer to vertical positions of the two platforms respectively; $x_{i,\min}$ and $x_{i,\max}$ respectively denote the lower limit and the upper limit of a position variable; $x_{1,\min}$ and $x_{1,\max}$ were set to 500 mm and 4 500 mm respectively, while $x_{2,\min}$ and $x_{2,\max}$ were set to 4 500 mm and 8 500 mm respectively; C = 1 500 mm; σ_{M} is the bending stress of girder face plates of transverse and longitudinal bulkheads, MPa, and the goal of the optimization is to minimize the maximum bending stress. The mathematical optimization model was solved by using the genetic algorithm; the roulette-wheel selection with a selection probability of 0.9, the multi-point crossover with a crossover probability of 0.8, and the real-value mutation with a mutation probability of 0.01 were adopted in the genetic algorithm (All the genetic algorithms involved in this paper were set with the above parameters). As for this mathematical optimization model, the number of individuals of the population was set to 50, and the condition for convergence termination was that 8 consecutive generations had the same optimal solution or the maximum number of generations reached 20.

2.2 Optimization results and relevant analysis

A master control program for optimization was written based on MATLAB to call the FE analysis software, ANSYS, for structural analysis. The optimization results were: x_1 = 2 900 mm, x_2 = 6 200 mm, $\min(\max(\sigma_M(X)))$ = 60 MPa, which meant that the lower platform was at a height of 2 900 mm, while the upper one was at a height of 6 200 mm. Under this arrangement, the maximum bending stress of the girder face plates of transverse and longitudinal bulkheads was 60 MPa. Compared with the initial simplification scheme, the optimization scheme reduced the stress by 31%, and the internal platforms were arranged approximately in a uniform manner.

3 Optimal design of internal pillars

In the case of the cabin under internal pressure, the surrounding transverse and longitudinal bulkheads and decks will deform significantly, with higher stress. The transverse and longitudinal bulkheads can be reinforced through the arrangement of internal platforms, and internal pillars arranged to connect the inner bottom with the top deck are used to reinforce the deck. However, too many pillars will result in excessive weight and affect the equipment arrangement in the cabin. In the case of variable numbers, positions, and dimensions of pillars, how to obtain the minimum weight of the pillars by taking the stress of the deck and pillar structures as the constraint condition is a problem to be solved in the optimal design of the internal pillars.

The optimization problem involves the selection of variables, as well as the permutation and combination of variables, and the permutation and combination problem will yield combinatorial explosions exponentially with the increase of the number of alternatives. In order to save calculation time, the problem was simplified and decomposed in this paper. In other words, the three variable parameters of pillar number, positions, and dimensions were optimized in different batches.

1) Given constant pillar number and dimensions and variable positions, minimize the maximum bending stress of the top deck so as to obtain optimal positions of pillars.

2) Change the number of pillars several times, and conduct Step 1) respectively. By comparing respective optimal results, select the one with the fewest pillars as the optimal scheme of pillar arrangement, under the condition of satisfying the stress limitation.

3) Based on the optimal pillar number and positions obtained from Step 2), by setting pillar dimensions as variables and pillar weight from Step 2) as constraints, minimize the maximum bending stress of the top deck to obtain optimal dimensional combination of pillars.

3.1 Mathematic model for optimization of internal pillars

3.1.1 Mathematic model for optimization of pillar arrangement

It is supposed that pillars have the same stiffness and are symmetrically arranged with respect to the platform center, and thus, the mathematic model for optimization of pillar arrangement can be given as follows:

$$\begin{aligned} &\text{Find: } \boldsymbol{X}=[x_1, x_2, \cdots, x_n]^{\mathrm{T}} \\ &\text{s.t. } x_i = 0\text{或}1\text{；} \quad i=1,2,\cdots,n \\ &\sum_{i=1}^{n} x_i = N \\ &\sigma_z(\boldsymbol{X}) \leqslant [\sigma] \\ &\min: \max(\sigma_{\mathrm{M}}(\boldsymbol{X})) \end{aligned} \qquad (2)$$

where x_i is a design variable of pillar positions, and there are totally 20 such variables in this example, as shown in Fig. 4, x_i being 0 means no pillar will be arranged, x_i being 1 means a pillar will be arranged; $\sum x_i$ denotes the sum of the number of pillars; N is the defined total number of pillars; pillars are round tubes with uniform section size of 203 mm×18 mm; $\sigma_z(\boldsymbol{X})$ is the maximum stress of pillars, MPa; $[\sigma]$ is the allowable stress of pillars, which was set to 300 MPa; $\sigma_{\mathrm{M}}(\boldsymbol{X})$ is the maximum bending stress of the top-deck girders, MPa. The mathematical optimization model was solved by using the genetic algorithm. In the algorithm, the number of individuals of the population was set to 500, the condition for convergence termination was that 8 consecutive generations had the same optimal solution or the maximum number of generations reached 50, other parameters were the same as those mentioned in Section 2.1.

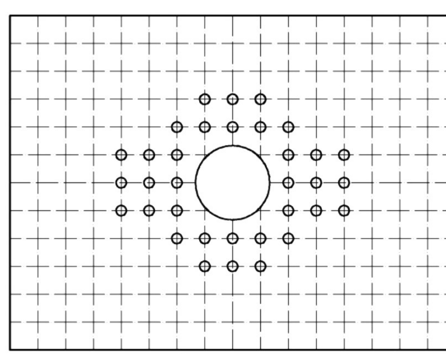


Fig.4 Diagram of the position of pillars (circle point in the diagram)

3.1.2 Mathematical model for the dimensional design of pillars

It is supposed that pillars are of unequal stiffness, and then, the mathematical model for the dimensional design of pillars can be given by:

$$\begin{aligned} &\text{Find: } \boldsymbol{X}=[x_1, x_2, \cdots, x_n]^{\mathrm{T}} \\ &\text{s.t. } x_i \in \{1,2,3,4,5,6\}; i=1,2,\cdots,n \\ &\sigma_z(\boldsymbol{X}) \leqslant [\sigma] \\ &\sum_{i=1}^{n} m(x_i) \leqslant W \\ &\min: \max(\sigma_{\mathrm{M}}(\boldsymbol{X})) \end{aligned} \qquad (3)$$

where x_i refers to sectional dimension of pillars and 1–6 in its value range represent the serial numbers of sectional dimensions of pillars, the corresponding sectional dimensions are 203 mm×14 mm, 203 mm×20 mm, 219 mm×14 mm, 245 mm×10 mm, 245 mm×12 mm, 299 mm×20 mm respectively; $\sum m(x_i)$ denotes the total weight of pillars; W is the total weight of pillars from the optimization result in Section 3.1.1, t. The mathematical optimization model was solved by using the genetic algorithm. In the algorithm, the number of individuals of the population was set to 50, the condition for convergence termination was that 8 consecutive generations had the same optimal solution or the maximum number of generations reached 30, other parameters were the same as those mentioned in Section 2.1.

3.2 Pillar optimization results and relevant analysis

The maximum bending stress of top-deck girders under optimal pillar arrangement was obtained by optimizing the pillar layout in terms of different numbers of pillars, as shown in Fig. 5.

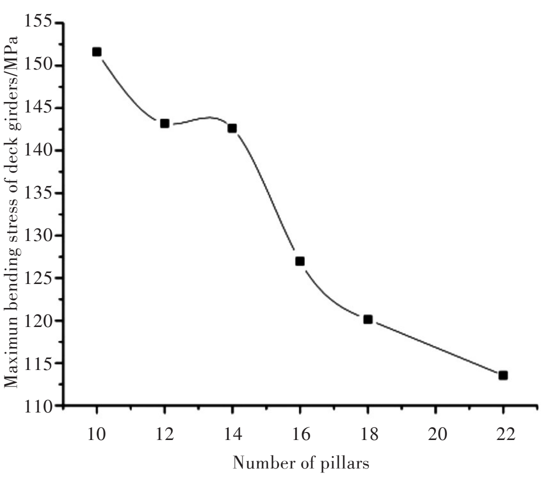
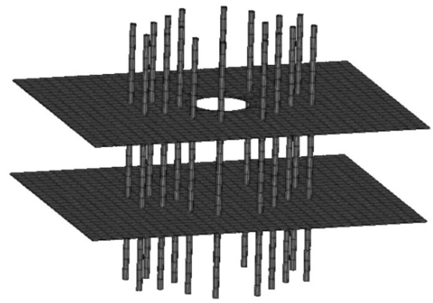
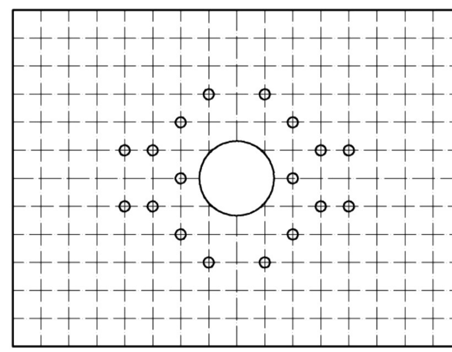


Fig.5 Maximum bending stress of deck girder under different number of pillars

As this example did not take into account other stress components, such as total longitudinal bending stress, the proportion of this stress should not be too high under internal pressure load, and the allowable stress was set to 122 MPa. According to Fig. 5 and the constraint on the bending stress of girders, it can be seen that when the minimum number of pillars is 18, the stress is the closest to the constraint value and satisfies the constraint condition, which is the optimal result of pillar arrangement. Under this arrangement, the maximum bending stress of the top-deck girders is 120.4 MPa, and the maximum stress of pillars is 204.4 MPa. Fig. 6 shows the optimal pillar layout.



(a) Stereogram



(b) Plan sketch

Fig.6 Sketch of optimal layout of pillars

From the optimal arrangement, pillars are axisymmetrically distributed in a relatively uniform manner. Fewer pillars are arranged around the round holes and on the two symmetry axes, and more pillars are arranged at the periphery in the range of optional positions.

Pillar dimensions were further optimized based on the pillar number (18) and the positions shown in Fig. 6. The relevant result is shown in Fig. 7 (digits in the figure refer to serial numbers of sectional dimensions). The bending stress of top-deck girders is 115.1 MPa, further reduced by 4.4% compared with that in the original optimization scheme, and the maximum stress of pillars in this case is 206.7 MPa, only increased by 1.1% compared with that in the original optimization scheme, which meets the stress-limit requirement.

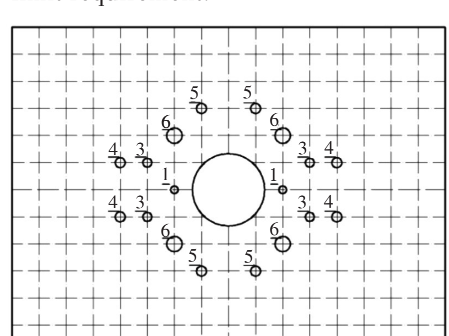


Fig.7 Sketch of optimum arrangement of pillars with different rigidity

Under comprehensive consideration, this layout of pillars with different sectional dimensions was deemed as the final result of the optimal design in this paper, as the optimal design mainly focused on the maximum bending stress of the top deck, and the stress of pillars met the stress-limit requirement. The optimization result was then applied to the original model of the whole structure for stress calculation, and relevant results were compared with those from the initial scheme, as shown in Table 1.

Table 1 Comparison of original and final optimization results

Hull structure	Stress values/MPa		Percentage of stress reduction/%
	Initial scheme	Optimal scheme	
Transverse bulkhead	82.9	59.4	28.3
Longitudinal bulkhead	87.0	64.6	25.7
Deck	138.6	119.4	13.9
Pillar	212.9	204.4	4.0

Comparison results show that the optimization scheme enables different levels of stress reduction of transverse and longitudinal bulkheads, decks, and internal pillars, with a relatively significant optimization effect.

4 Conclusion

Layouts of internal platforms and pillars of a rectangular cabin under internal pressure have been optimally designed, and the optimization results can effectively reduce bending stress of the bulkheads and the top deck. Major conclusions are as follows:

1) Mathematical optimization models in this paper are reasonably designed, which can be used to obtain optimal vertical positions of internal platforms and optimal positions and sectional dimensions of pillars, with a significant optimization effect.

2) The rearrangement of internal platforms from initial positions to approximately equidistributed positions makes the bending stress of the transverse and longitudinal bulkheads reduce by 28.3% and 25.7% respectively.

3) Pillars in the optimal layout are relatively scattered, with a relatively uniform separation distance; pillars with higher stiffness are mainly arranged near the center. The bending stress of the top deck in the optimization scheme is 13.9% lower than that in the initial scheme.

The two methods for optimal design, proposed in this paper, have yielded effective optimization results and thus can provide reference for solving similar problems in structural design.

References

[1] ZHAO L P, ZHAN D W, CHENG Y S, et al. Review on optimum design methods of ship structures[J]. Chinese Journal of Ship Research, 2014, 9(4): 1-10 (in Chinese).

[2] SEKULSKI Z. Structural weight minimization of high speed vehicle-passenger catamaran by genetic algorithm[J]. Polish Maritime Research, 2009, 16(2): 11-23.

[3] KLANAC A, JELOVICA J. A concept of omni-optimization for ship structural design [C]//Proceedings of MARSTRUCT Advancements in Marine Structures. Scotland: [s.n.], 2007: 473-481.

[4] CHENG Y S, YOU J J. Optimization of docking block placement and dimensions[J]. Journal of Ship Mechanics, 2004, 8(2): 63-70 (in Chinese).

[5] CHENG Y S, ZENG G W. Optimum disposition of wooden blocks during ship ducking[J]. Shipbuilding of China, 1995(1): 18-27 (in Chinese).

[6] YANG D Q, MA T, CHEN W, et al. Optimal allocations of seismic restraints in pipeline system in ships by code method[J]. Shipbuilding of China, 2012, 53 (1): 62-78 (in Chinese).

[7] CUI J J, WANG D Y, SHI Q Q. Structural topology design of container ship based on knowledge-based engineering and level set method[J]. China Ocean Engineering, 2015, 29(4): 551-564.

[8] SEKULSKI Z. Multi-objective topology and size optimization of high-speed vehicle-passenger catamaran structure by genetic algorithm[J]. Marine Structures, 2010, 23(4): 405-433.

[9] SEKULSKI Z. Least-weight topology and size optimization of high speed vehicle-passenger catamaran structure by genetic algorithm [J]. Marine Structures, 2009, 22(4): 691-711.

[10] QIAN Y, WANG D Y. Optimization design of ship engine room structures based on sectionalized dynamic relaxation collaborative optimization method[J]. Chinese Journal of Ship Research, 2016, 11(6): 40-46 (in Chinese).

[11] GAO S D, CHEN J, LU J F, et al. Shape and topology optimization design of rectangular tank's corner structure under internal pressure[J]. Shipbuilding of China, 2017, 58(1): 94-100 (in Chinese).

内压下矩形耐压舱内部结构优化设计

陈杨科[1,2], 余恩恩[1], 骆伟[3], 王红旭[3], 程远胜[1]
1 华中科技大学 船舶与海洋工程学院,湖北 武汉 430074
2 海军装备部 驻武汉地区军事代表局,湖北 武汉 430064
3 中国舰船研究设计中心,湖北 武汉 430064

摘　要:[**目的**]为有效降低内压下矩形耐压舱板架弯曲应力,[**方法**]分别提出内压下矩形耐压舱内部平台位置和支柱布局以及尺寸优化设计数学模型。以内部平台垂向位置作为设计变量,极小化横纵舱壁结构的最大弯曲应力,采用遗传算法求解,得到最优的内部平台布置位置,其优化结果接近垂向均布。支柱设计采用分级优化设计方法,先以等刚度支柱位置作为设计变量,极小化顶甲板结构的最大弯曲应力,分别得到不同支柱数量下的最优布局方案;然后依据应力约束条件选取支柱数量及布局,在此基础上进一步以支柱截面尺寸作为设计变量,以基础优化方案的重量作为约束,极小化顶甲板结构的最大弯曲应力,得到不等刚度支柱最优截面尺寸。[**结果**]其优化结果显示偏中心区域支柱截面积更大。最终优化设计方案较初始方案,横舱壁、纵舱壁和顶甲板弯曲应力分别降低了28.3%,25.7%和13.9%。[**结论**]本优化设计方法可为类似结构设计提供方法参考和设计借鉴。

关键词:内压矩形耐压舱;优化设计;内部平台;支柱布局

[*Continued from page* 7]

水上机场助航波能灯浮标的波能俘获优化

王广大[1], 毛筱菲[1,2]
1 武汉理工大学 交通学院,湖北 武汉 430063
2 高性能舰船技术教育部重点实验室,湖北 武汉 430063

摘　要:[**目的**]为了对水上机场波能灯浮标进行设计优化,以工作于沿海水上机场的阵列式助航波能灯浮标为研究对象,提出一种小型阵列式浮标的优化设计方法。[**方法**]基于三维势流理论,计算浮标的垂荡运动响应,在满足最佳能量转换部分(PTO)阻尼匹配的情况下,得到使能量俘获宽度比最大的浮标直径吃水比和浮标间距,然后对单个浮标的能量俘获进行短期预报,并在此基础上结合实际海况对阵列式浮标的能量俘获进行长期预报,分别讨论浮标直径、吃水和浮标间距对阵列式浮标能量俘获的影响。[**结果**]结果表明,当单个浮标直径吃水比为2.4~2.6时,能量俘获宽度比最大;阵列浮标间距越小,阵列式助航波能灯浮标的能量俘获宽度比越大。[**结论**]所做的工作可为阵列式波浪能发电装置的设计优化提供一定的参考和建议。

关键词:阵列式浮标;PTO阻尼;能量俘获宽度比;水上机场