

Static and dynamic collaborative optimization of ship hull structure

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Abstract: The goal of this effort was to provide a static and dynamic collaborative optimization (CO) model for the design of ship hull structure. The CO model integrated with static, mode and dynamic analyses. In the system-level optimization model, a new objective function was advised, integrating all the subsystem-levels' objective functions, so as to eliminate the effects of dimensions and magnitude order. The proposed CO architecture enabled multi-objectives of the system and subsystem-level to be considered at both levels during optimization. A bi-level optimization strategy was advised, using the multi-island genetic algorithm. The proposed model was demonstrated with a deck optimization problem of container ship stern. The analysis progress and results of example show that the CO strategy is not only feasible and reliable, but also well suited for use in actual optimization problems of ship design.

Keywords: collaborative optimization; multi-island genetic algorithm; static analysis; dynamic analysis

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1 Introduction

It is desirable to minimize the weight of ship structure to reduce the cost, and minimize the dynamic responses of maritime vessels, so as to improve passenger comfort, and in the case of naval vessels, to avoid being detected. The optimization technology is necessary. The ship structural optimization is to determine the size of plates and frames so as to obtain the maximum performance using minimal cost. M.M. Alinia optimized the stiffeners in plates subjected to shear loading^[1]. O.J. O'Leary *et al* studied the optimization problem of stiffened panel with fundamental frequency constraint^[2]. Paul G. Dylejko *et al* optimized the resonance changer configurations in a submarine to minimize the vibration transmission^[3]. For avoiding the sympathetic vibration, the optimization method with frequency preserve can be used under the dynamic load^[4].

In most optimization problems, the minimum structural weight has attracted much attention in many applications for various reasons. But the feasibility is worthy of deliberation that structural weight is selected as the objective function in the dynamic optimization^[5]. That is, different objective functions may be used in different disciplinary optimization models. So the optimization problem about ship structural static and dynamic properties is a multi-objective optimization problem.

There are several efforts to solve multi-objective optimization problems, such as the multi-objective collaborative optimization (MOCO) method^[6,7], and the multi-objective multidisciplinary genetic algorithm method^[8]. The multi-objective function was transformed to a single objective function with the weighted method^[6]. In this model, the dimension of the system level problem is equivalent to that of the original problem (i.e., single level optimization). At the same time, the consistency constraints should use equality constraints. Multiple system-level objectives were integrated in terms of physically meaningful parameters^[7]. An agent-based structural static and dynamic collaborative optimization system was constructed as two agent colonies^[9]. When the objective functions have different dimensions and magnitude orders, some difficulties will be encountered in the process of optimization.

The collaborative optimization (CO) is characterized by a distributed, bi-level structure, wherein a system problem seeks to optimize system performance, whereas disciplinary problems attempt to minimize the interdisciplinary inconsistency in the variables and responses shared by the disciplines. The CO method has been successfully used in many cases. However, the computational difficulties in CO have also been observed. The reason was found that the difficulties are caused by the use of equality forms for the system-level consistency constraints^[10-11]. The consistency equality constraints make it hard to find a solution satisfying both the Kuhn-Tucker conditions and the consistency constraints. To solve this problem, the system-level equality

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constraints are modified with a relax factor^[10], or the penalty-function method^[11].

The goal of this work is to develop a static and dynamic CO model used in ship structural design. The improved CO model includes static, mode and dynamic optimization. A bi-level optimization strategy is advised for solving the present problem. Last, an example is used to check the proposed CO model and optimization strategy.

2 Static and dynamic collaborative optimization model

2.1 Subsystem-level optimization

In the standard CO algorithm, the subsystem-level objective function is an objection of consistency constraints, but in this paper, it is an objective function of the single disciplinary optimization model which is independent of the consistency constraints.

2.1.1 Shared size constraints

The shared size constraints are the restricted conditions coming from the rules. The design rules give the minimum allowance sizes and other size constraints decided by production technology, the usage requirement or material property and so on. There are physical limitations for the shared design variables.

$$x_i - x_{i,\min} \geq 0 \quad x_{i,\max} - x_i \geq 0 \quad (i=1, \dots, n) \quad (1)$$

where $x_{i,\max}$ and $x_{i,\min}$ are the upper and lower bounds of the design variable x_i , respectively. The rules give the deterministic prescript to the size of various plates and frame of ship hull structure. For the undescribed sizes, we will give their limit according to the parent ship.

2.1.2 Static optimization

1) Objective function.

It is the target of static optimization on ship hull structure to lighten the weight of structure more efficiently and make stress distribution more rational. So we select minimum weight as the objective function

$$\text{Minimize } F_1 = \text{Weight} \quad (2)$$

where F_1 is the total weight of structure.

2) Constraints.

Constraints are the strength conditions for taking full advantage of mechanical property of materials. So the maximum stress must not be larger than the corresponding allowable design stress. The constraints are

$$\sigma_{\max} - [\sigma] \leq 0 \quad \tau_{\max} - [\tau] \leq 0 \quad (3)$$

where σ_{\max} and τ_{\max} are the maximum von Mises stress or normal stress and shearing stress, respectively. $[\sigma]$ and $[\tau]$ are the allowable design stress.

2.1.3 Mode optimization

1) Objective function

Resonance vibration will appear easily when the first natural frequency of ship hull structure has lower value. So the target of mode optimization is how to get the maximum first natural frequency. The objective function is

$$\text{Maximize } F_2 = 1^{\text{st}} \text{ natural frequency} \quad (4)$$

where F_2 is the first natural frequency of structure.

2) Constraints

Sympathetic vibration can be avoided in a limited extension, if we give the ship hull structure some restrictions and ensure the natural frequency has deviation value with the excitation frequency. We usually concern the first three natural frequencies, so the constraints are the first three frequency preserve as follows:

$$\begin{cases} (1-\alpha)N_1 \leq n \leq (1+\alpha)N_1 \\ (1-\beta)N_2 \leq n \leq (1+\beta)N_2 \\ (1-\gamma)N_3 \leq n \leq (1+\gamma)N_3 \end{cases} \quad (5)$$

where $N_i (i=1,2,3)$ are the first three natural frequencies of structure. n is the excitation frequency. α , β and γ are the parameters reflecting the bound of frequency preserve. The rules give the deviation value between the first three natural frequencies and the excitation frequencies. They are $\pm 10\sim 15\%$, $\pm 15\sim 20\%$ and $\pm 20\sim 30\%$.

2.1.4 Dynamic optimization

1) Objective function

The sailormen and passengers will feel worse and the machine may not work normally when the vibration appears furiously. In some bad circumstance, some cracks or fatigue failure in component will appear. So we have to reduce the response amplitude of the structure. The objective function is

$$\text{Minimize } F_3 = a_{\max} \quad (6)$$

where F_3 is the maximum acceleration of ship hull structure.

2) Constraints

When the acceleration has minimum value, the velocity of ship hull structure has to satisfy corresponding constraint, i.e.

$$v_{\max} - [v] \leq 0, \quad (7)$$

where v_{\max} is the maximum velocity of ship hull structure; $[v]$ is the allowable design velocity.

2.2 System-level optimization

1) Objective function.

The goal of the system-level optimizer is to get an optimal system level objective function value while satisfying consistency constraints. In the standard CO algorithm, the system-level objective function is a single

objective function. Some difficulties will be encountered in handling the above sub-problems. There are three different objectives. On the other hand, they have not only different dimensions (the units of mass, frequency and acceleration are kg, Hz and m/s^2 , respectively), but also different magnitude orders. For eliminating those effects, the relative values are used in the system-level objective function.

In the process of optimization, the design variables in different disciplinary models might have different values, because all of design variables will change during the optimal design and they are controlled by their disciplinary constraints and objective function. Since the same value of shared variables in the final design, all the subsystems have to come to comprise each other. So the optimum solution coming from single disciplinary optimization model is prior to the multidisciplinary optimum solution. The goal of the system-level optimization model is how to minimize the discrepancy of those solutions. The system objective function is

$$\text{Minimize } \left| \frac{F_1(z) - F_1^*}{F_1^*} \right| + \left| \frac{F_2(z) - F_2^*}{F_2^*} \right| + \left| \frac{F_3(z) - F_3^*}{F_3^*} \right|, \quad (8)$$

where $F_i(z)$ ($i=1,2,3$) is the i th disciplinary computed solution in the system-level model directly coming from disciplinary analysis. F_i^* ($i=1,2,3$) is the subsystem-level optimum solution in its disciplinary optimization model lonely.

2) Constraints.

To avoid no-solution or convergence difficulties, the consistency constraints are replaced by the inequalities, that is

$$J_i(z) = \sum_{j=1} (x_{j1} - z_1)^2 + \sum_{k=1} (x_{k2} - z_2)^2 \leq \varepsilon \quad (i=1,2,3), \quad (9)$$

where $J_i(z) \leq \varepsilon$ is the inequality consistency constraint; ε is the relax factor. $z=\{z_1, z_2\}$ is the system-level design variable; z_1 is the shared design variable; z_2 is the coupling design variable; x_{j1} is the global design variable; x_{k2} is the state design variable

2.3 Interdisciplinary coupling

The interdisciplinary coupling structure is shown in Table 1. Here the I/O relationship between design variables and disciplinary analysis models is depicted.

Table 1 Interdisciplinary coupling depiction

Parameters	Static analysis	Mode analysis	Dynamic analysis
Shared design variable	input	input	input
Weight	output	output	output
Stress	output		output
Displacement	output		output
Frequency		output	output
Velocity			output
Acceleration			output

2.4 Collaborative optimization architecture

The static and dynamic CO architecture proposed in this paper is depicted as Fig.1. Here, the design is decomposed into three modules which are static, mode and dynamic optimization, and coordinated by a system-level optimization procedure.

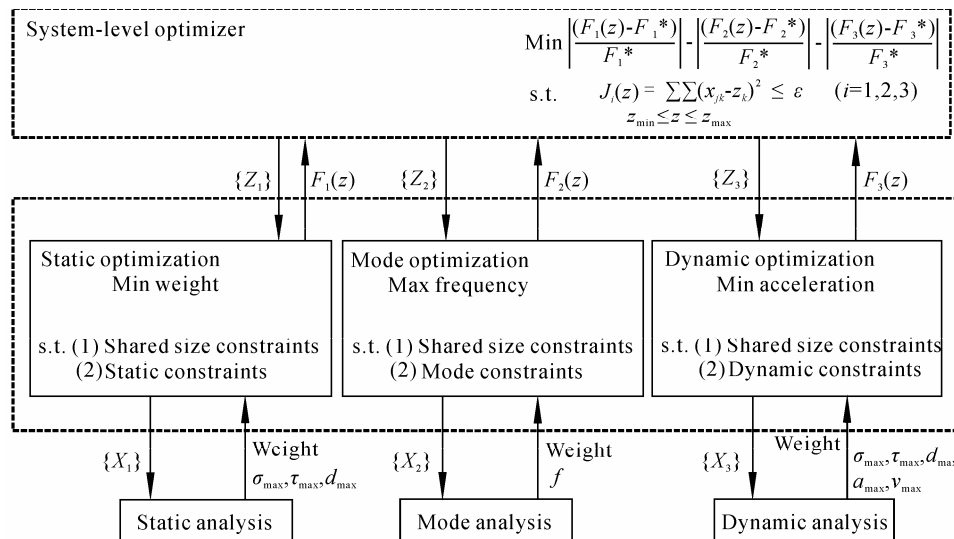


Fig.1 Static and dynamic CO architecture

3 Optimization strategy

The algorithms are evaluated based on the solution quality and computation time. Each algorithm is analyzed for its ability to handle various variables, deterministic constraints and stochastic constraints.

The design variables in ship hull structure optimization model are the sizes of plates and frames. We can only choose the sizes of ship plates and shipbuilding sections defined by the rules, and can not select any real number. So the design variables belong to discrete variables.

The optimization search techniques can be classified as local or global. The multi-island genetic algorithm (MIGA) is well-suited for discontinuous design spaces, and it belongs to global optimization search technique and can find the global optimum solution from the whole design space. The MIGA is used in the system and subsystem-level's optimization models, so the optimization search method in this work is a bi-level optimization method.

4 Numerical example

The deck of 3100 TEU container ship stern is used to check the proposed CO model and optimization strategy. The aftership structure, from FR-12 to FR+10, is modeled as a mesh in details by finite element method, as shown in Fig.2. Half of deck (port side) is used in FEM model because the type of structure and load are symmetric about midship section. The model has 1 440 nodes and 2 246 elements including 1 352 shell elements and 894 beam elements with offsetting of bending center. The symmetrical boundary condition is used in the side of midship section. And the simple boundary condition is used in the other three sides. The thickness of plates, from 0 to 13.68 m along y axis, is 12 mm. The thickness of other plates is 15 mm each. There are 5 T-section steels and 13 L-section steels in the longitudinal frame, and 6 T-section steels in transverse frame. Young's modulus is 206 GPa, Poisson's ratio is 0.3. The mass density of the structure is 7 850 kg/m³. The damping coefficient is 0.001. The range of the 1st natural frequency value is from 10.0 Hz to 13.0 Hz. The lower bound of the 2nd and 3rd natural frequencies is 21.66 Hz. The upper bound of vertical acceleration is 0.025 g. The allowable design stress of computational case is decided by the guidelines for direct strength analysis of container ship of CCS.

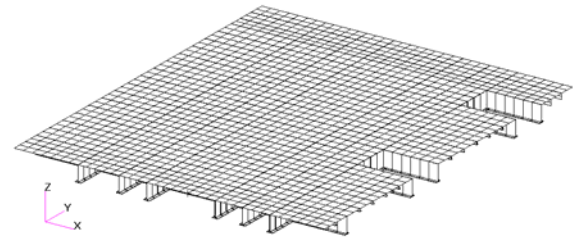


Fig.2 Finite element mesh

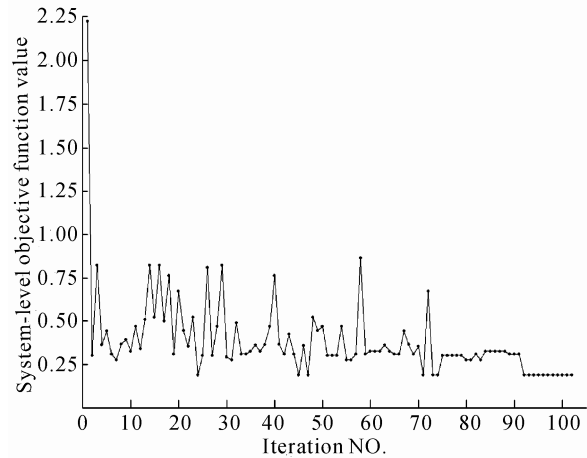


Fig.3 System-level objective function history

4.1 Design variables

All the sizes and thicknesses of plates and the section size of section steels are the design variables for thinking full over the effects of various variables to the design responses. The total number of design variables is 8, as shown in Table 2.

Table 2 Comparison between the initial and final design variables

Design variable		Initial design /mm	Final design /mm
Plate/15mm	x_1	15	11
Plate/12mm	x_2	12	11
L125 × 80 × 12	x_3	125	100
	x_4	80	70
	x_5	12	10
700 × 12 250 × 12	x_6	700	650
	x_7	250	230
	x_8	12	12

4.2 Optimization strategy

The parameters of the MIGA are as follows: the sub-population size is 10.0; the number of generations is 10.0; the number of islands is 10.0; the rate of crossover is 1.0; the rate of mutation is 0.01; the rate of migration is 0.01; the interval of migration is 5.0; elite size is 1.0.

4.3 Results

The final design is reached after 102 collaborative

iterations. The iteration history of system-level objective function is drawn in Fig.3. The optimum solution of various design variables is shown in Table 2 too. The values of the initial and final responses are shown in Table3.

Table 3 Comparison between the initial and final design responses

Design response		Initial design	Final design
Static response	σ_{\max}/MPa	126.94	142.99
	d_{\max}/m	0.069	0.073
Mode response	f_1/Hz	11.73	11.90
	f_2/Hz	26.27	26.43
	f_3/Hz	28.84	27.32
Dynamic response	$v_{\max}/(\text{m/s})$	0.002 5	0.002 6
	$a_{\max}/(\text{m/s}^2)$	0.131	0.132
Mass /kg		39 712.96	35 769.18

This optimization problem is nonlinear and involves discrete variables. The following conclusions can be drawn from the present study.

1) The deck design problem is solved successfully by the CO model proposed in this paper. Successful convergence proves the feasibility and reliability at both system and subsystem levels.

2) After the design variables have changed, all the final design response values satisfy the constraints. The maximum stress of final design, 142.99 MPa, is less than the allowable design stress. The first natural frequency increases from 11.73 to 11.90 Hz. Because the shape of structure is determined before structural design, the effect of size change is limited. The 2nd and 3rd natural frequencies are larger than 21.66 Hz each. The values of acceleration and velocity have a little increase, but they are far away from the lower limit given by the rules.

3) The total mass decreases from 39 712.96 to 35 769.18 kg, reducing about 9.93%. For a container ship, it is very practicable and economical because it can greatly reduce cost.

5 Conclusions

An attempt has been made in this work to establish a new CO model of ship design for combination of static, mode and dynamic properties. This improved model has some remarkable characters as follows:

1) It enables multiple objectives of the system and subsystem-level to be considered at both levels during optimization.

2) The new system-level objective function not only

minimizes the difference of the optimum solution between the multidisciplinary and single disciplinary analysis, but also eliminates the effect of different dimensions and magnitude orders among objectives.

3) A bi-level optimization strategy is advised which uses the MIGA.

The analysis progress and results of deck show that the improved CO model and optimization strategy proposed in this paper are feasible and reliable, and are well suited for use in actual optimization problem of ship structure design.

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船体结构静动态协同优化设计

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摘 要: 论文集成静态、模态和动力响应分析, 建立了船体结构静、动态协同优化模型. 在系统级优化模型中, 以单学科最优解和多学科最优解之间的差异最小化为目标. 该目标函数不仅消除了多个目标之间的量纲和数量级差异的影响, 而且扩展了协同优化算法的应用范围, 由原来的单目标优化扩展到了多目标优化. 并与子系统级优化模型构成二级协同优化算法架构. 采用多岛遗传算法进行优化求解. 对集装箱船艉主甲板进行了静、动态优化设计, 分析表明本文所采用的优化算法能应用于工程实际.

关键词: 协同优化; 多岛遗传算法; 静态分析; 动态分析