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Optimization of ship inner shell to improve the safety of seagoing transport ship

Yan-Yun YU and Yan LIN

State Key Laboratory of Structural Analysis for Industrial Equipment,
Dalian University of Technology, Dalian, China

ABSTRACT: *A practical Ship Inner Shell Optimization Method (SISOM), the purpose of which is to improve the safety of the seagoing transport ship by decreasing the maximum Still Water Bending Moment (SWBM) of the hull girder under all typical loading conditions, is presented in this paper. The objective of SISOM is to make the maximum SWBM minimum, and the section areas of the inner shell are taken as optimization variables. The main requirements of the ship performances, such as cargo hold capacity, propeller and rudder immersion, bridge visibility, damage stability and prevention of pollution etc., are taken as constraints. The penalty function method is used in SISOM to change the above nonlinear constraint problem into an unconstrained one, which is then solved by applying the steepest descent method. After optimization, the optimal section area distribution of the inner shell is obtained, and the shape of inner shell is adjusted according to the optimal section area. SISOM is applied to a product oil tanker and a bulk carrier, and the maximum SWBM of the two ships is significantly decreased by changing the shape of inner shell plate slightly. The two examples prove that SISOM is highly efficient and valuable to engineering practice.*

KEY WORDS: Ship; Safety; Inner shell plate; Optimization design; Still water bending moment.

ABBREVIATIONS

SISOM	Ship Inner Shell Optimization Method	ISP	Inner Shell Plate
SWBM	Still Water Bending Moment	LCV	Longitudinal Center of Volume
SWSF	Still Water Sheer Force	MMLC	Maximum bending Moment Loading condition
CH	Cargo Hold	HTSP	Hopper Tank Sloping Plate
WBT	Water Ballast Tank	TWSP	Topside Wing tank Sloping Plate
GA	Genetic Algorithm		

INTRODUCTION

The SWBM is a major component of the hull girder bending moment, and it is very important to the structural strength of transport ship. Large SWBM will cause several types of hull structure failures, such as fatigue crack, local buckling deformation, or even catastrophic incidents. According to the report provided by Shipping Statistics and Market Review, there were 661 ships, 51.4% of which are bulk carriers or oil tankers, are total loss because of founderings and weather during 1989 and 2005. In those total loss ships, the age of which are less than 10 years occupies only 11%, while most of the ships are built more than 15 years ago. From this data, it can come to a conclusion that most of these ships are not lost due to loss of stability

Corresponding author: *Yan-Yun YU*
e-mail: *yuyanyun@dlut.edu.cn*

or operation faults, but because of the weakening of global strength after years of structure corrosion. There are two ways to improve the safety of ship during its whole life cycle. One is to reinforce the hull structure maintenance, especially structure corrosion prevention. The other is to enhance the ability of ship to survival more extreme sea conditions at the design stage, such as increasing the plate thickness or decreasing SWBM, and the latter is more effective and economical than the former.

There are many researches on how to decrease the maximum SWBM of ship with optimum design in the previous literatures. Ivanov and Wang (2007) proposed an simplified Still Water Sheer Force (SWSF) and SWBM calculating method, which is used in ship tank subdivision with the bulkhead positions as variables; Chen et al. (2010) proposed a tank subdivision optimazation methods based on Genetic Algorithm (GA) to minimize SWBM under sequential ballast water exchange condition; Lin et al. (1994) put forward a neural network expert system, which is applied for the intelligent design of ship and optimum tank subdivision. These researches are effective for reducing the maximum SWBM, but still, they have the following shortages:

(1) The existing literatures are all aimed at the optimum design of the transverse bulkhead position, and they are able to decreasing the maximum SWBM in part loaded conditions such as ballast water exchange condition, heavy ballast condition, and heavy cargo alternate loading condition etc. However, they are invalid for the full load and normal ballast condition, in which SWBM has nothing to do with the transverse bulkhead position. For the ship the maximum SWBM of which appears in normal loading condition or full loading condition, the existing method could not reduce the maximum SWBM of the hull.
(2) In the existing methods, only one loading condition is considered in their optimization model, which will cause the performance of ship under some other loading conditions not satisfying the requirements. That means those methods could not ensure the feasibility of the optimum solution.

Generally, the seagoing oil tankers and bulk carriers have double bottom and double shell (or single shell but with hopper tank and topside wing tank, such as single shell bulk carrier). That is to say, the cargo hold segment of these ships consists of two layers. One is the outer shell including outer bottom and outer side shell. The other one includes the inner bottom plate, hopper tank sloping plate, double shell plate, topside tank sloping plate etc., and they are called Inner Shell Plate (ISP) for short. ISP is the boundary of Cargo Hold (CH) with Water Ballast Tank (WBT). In this paper, cargo hold and cargo oil tank are all called CH for convenience. As a result, the shape of ISP is a predominant influence on the weight distribution of both cargo/cargo oil and water ballast under each loading condition. As the maximum SWBM is closely related to weight distribution, so it is an effective way to decrease the maximum SWBM by shape optimization of ISP. On this base, the Ship Inner Shell Optimization Method (SISOM), which is used to minimize the maximum SWBM of the seagoing transport ship under all typical loading conditions, is presented in this paper.

To make the optimum solution feasible, there are several requirements that should be always satisfied. For the transport ships, sufficient CH capacity is a basic functional requirement. Under ballast conditions, ship should have adequate aft draft to meet the requirement of propeller and rudder immersion. However, aft trim is not the lager the better, for large aft trim is unfavorable to bridge visibility. So the draft and trim should in an appropriate range, which requires that the ship should have not only sufficient WBT capacity, but also proper Longitudinal Center of Volume (LCV) for all WBTs. For the oil tanker, ISP should meet the requirement of permanent means of access as described in SOLAS (2004), and the minimum requirement of pollution prevention of MARPOL (2001) should also be satisfied. In addition, ISP should fulfill the request of construction technology. All the above requirements should be satisfied in ISP shape optimization.

The main object of this paper is to propose the objective model for SISOM, solve the optimization problem and apply the method in engineering practice. This paper is organized as follows: in section 2, the mathematical optimization model of SISOM is proposed and explained in detail; the solution of the optimization model is discussed in section 3; two applications of SISOM, one is the optimization design for a 26,000 DWT product oil tanker, and the other is for a 69,000 DWT bulk carrier, are introduced with the purpose of explaining how to use SISOM in engineering practice; section 5 is a brief conclusion of SISOM.

MATHEMATICAL MODEL OF SISOM

The purpose of SISOM is to decrease the maximum SWBM under all typical seagoing loading conditions via shape optimazation of ISP, on condition that all the safety and function requirements are satisfied. As to most of the seagoing oil tanker and bulk carrier, there is a loading condition, the maximum SWBM of which is significantly larger than that of the other loading conditions significantly. This loading condition is called Maximum bending Moment Loading Condition (MMLC) in this paper.

For example, MMLC for 20,000-80,000 DWT oil tankers is ballast departure loading condition, and MMLC for 65,000-80,000 DWT bulk carriers is heavy cargo alternate loading condition etc. Even though the maximum SWBM of typical loading conditions could be changed via ISP or subdivision optimization, MMLC still has the largest maximum SWBM for those ships. As a result, reducing the maximum SWBM under MMLC is equivalent to reducing that of all typical loading conditions. So SISOM takes the absolute of maximum SWBM under MMLC as objective function.

For convenience of design and construction, all ISP should be planar. Along ship length direction, ISP should have several corner positions, where at least one plate of ISP has a corner. Those positions are called Corner Positions for short in this paper. Assume that the bulkhead position and the corner positions of ISP keep unchanged, then the capacity distribution of CHs as well as WBTs is determined by the section areas of ISP at corner positions, and so is the maximum SWBM of MMLC. SISOM take the section areas of ISP at corner positions as variables, and create the optimization model for SISOM as follows:

$$\begin{cases} \min\ \max\left(f(x,\mathbf{A}) = \left| \int_a^x \int_a^y B(t,\mathbf{A}) - LW(t) - DWT(t)dtdy \right| \right) \\ \text{s.t. a.} \int_a^f \left(B(x,\mathbf{A}) - LW(x) - DWT(x) \right) dx = 0 \\ \quad \text{b.} \int_a^f \left(B(x,\mathbf{A}) - LW(x) - DWT(x) \right) x dx = 0 \\ \quad \text{c.} \sum_1^{n-1} \frac{(A_i + A_{i+1})}{2} \cdot (X_{i+1} - X_i) = C_c \\ \quad \text{d.}\ XB_{\min} \le \dfrac{\sum_1^{n-1} (2S_i - A_i - A_{i+1}) \cdot (X^2{}_{i+1} - X^2{}_i)}{2\sum_1^{n-1} (2S_i - A_i - A_{i+1}) \cdot (X_{i+1} - X_i)} \le XB_{\max} \\ \quad \text{e.}\ XC_{\min} \le \dfrac{\sum_1^{n-1} (A_i + A_{i+1}) \cdot (X^2{}_{i+1} - X^2{}_i)}{2\sum_1^{n-1} (A_i + A_{i+1}) \cdot (X_{i+1} - X_i)} \le XC_{\max} \\ \quad \text{f.} \sum_{i=1}^{\frac{m+1}{2}} V_{c2i} = C_h \\ \quad \text{g.}\ XH_{min} \le \dfrac{\sum_{i=1}^{\frac{m+1}{2}} V_{c2i} \cdot X_{c2i}}{\sum_{i=1}^{\frac{m+1}{2}} V_{c2i}} \le XH_{max} \\ \quad \text{h.}\ 0 < A_i < A_{i\max} \\ \quad \text{i.}\ A_{pa} = A_{pa+1} \end{cases} \tag{1}$$

where $A = (A_1, A_2, \ldots A_n)$ is the section area of ISP at corner positions, n is the number of the corner positions, m is the number of CHs, $X = (X_1, X_2, \ldots X_n)$ is the X coordinate of the corner. a and f is the aft and fore end position of hull respectively. $S = (S_1, S_2, \ldots S_n)$ is the transverse section area of the hull surface at the corner position. $LW(x)$ and DWT(x) is the light ship gravity and deadweight distribution function respectively. Deadweight consists of cargo/oil, ballast water, fuel oil, fresh water etc. $B(x,A)$ is the distribution curve of buoyancy according to the corresponding floating condition. $XB_{\min}$ is the lower LCV limit for all WBTs, and $XB_{\max}$ is that of the upper limit. Similarly, $XC_{\min}$ and $XC_{\max}$ is the lower limit and upper limit for LCV of all CHs respectively. V_{ci} and X_{ci} are the volume and LCV of the i^{th} CH respectively. C_c is the total volume of CHs. C_h is the total volume of the heavy CHs. Heavy CHs are the one with odd number generally. $XH_{\min}$ and $XH_{\max}$ are the lower and upper LCV limit of heavy CHs respectively. pa ($0<pa<n$-1) is the position index for the aft end of the parallel middle body, which means X_{pa} and X_{pa+1} is the aft position and fore position of parallel middle body respectively.

In the objective function, $f(x,\mathbf{A})$ means SWBM of hull girder at longitudinal position x under MMLC according to section area **A**. So the objective function means the maximum SWBM under MMLC. There are nine constraints, the means of which are as follows:

(1) Gravity-buoyancy balance of the hull.
(2) Moment of gravity-buoyancy balance of the ship.
(3) The total volume of CHs keeps unchanged. As the hull surface as well as bulkhead position is specified in SISOM, the total volume of all CHs and WBTs is fixed. So this constraint also means the total volume of WBTs keeps unchanged too.

(4) If deadweight is specified under a loading condition, the draft and trim of ship is mainly determined by LCV of the cargo or ballast water. For normal ballast loading condition, the LCV of WBTs should not be greater than XB_{max} to guarantee propeller and rudder immersion, and it should not be smaller than XB_{min} to avoid wave slap on the fore end of hull, or to avoid influence of bridge visibility.
(5) Being similar with the normal ballast loading condition, LCV of all CHs should be smaller than the upper limit XC_{max}, and greater than the lower limit XC_{min}.
(6) If the ship has heavy cargo alternate loading condition, the total volume of the heavy CHs should keeps constant. This constraint is invalid if no such loading condition exists for the ship.
(7) If the ship has heavy cargo alternate loading condition, the LCV of all heavy CHs should be within the range of [XH_{min}, XH_{max}] to get proper floating condition. This constraint is invalid if no such loading condition exists.
(8) ISP should meet the minimum requirements of pollution prevention and damage stability, which means the distance between each plate in ISP with the hull surface, should not be smaller than its lower limit. And because the hull surface is not changed, the section area of ISP at the i^{th} corner position, A_i , has upper limit A_{imax}, that is $A_i \le A_{imax}$ $(1 \le i \le n)$. Obviously, A_i should be greater than zero.
(9) The section area at the aft end and fore end of parallel middle body is A_{pa} and A_{pa+1} respectively. A_{pa} and A_{pa+1} are set to be equal. This constraint ensures that the transverse section of ISP keeps unchanged in the range of parallel middle body.

There are more requirements that must be satisfied than that stated above, such as intact stability, damage stability, service speed, seakeeping etc. Nevertheless, SISOM assumes that only the shape of ISP could be modified slightly, while all the other part of the design scheme, such as principal dimensions, structure that is uncorrelated to ISP, and hull surface etc, remain unchanged after optimization. As a result, SISOM will not affect the above performances remarkably, which means it is not necessary to take those requirements into account in the optimization process. After taken those factors into count, the optimization becomes a multi variable, multi nonlinear constraints, and nonlinear optimization problem. The next task is how to solve the optimization model.

SOLUTION OF THE OPTIMIZATION MODEL

SISOM has a complex objective function, and the non-linear constraints greatly increase the complexity of the optimization model. It could not be proved that SISOM has the unique optimum solution. On the contrary, there may be quite a lot of exreme values for the optimization model. As to most of the transport ship, ISP before optimization is a satisfactory solution consiering all design factors, and the less modification of ISP, the more beneficial to the productivity in design and production stage. As a result, the global optimum solution is the most important one mathematically, but the local optimum one that closest to the oriinal ISP is of great importance to engineering.

Theoretically, the evolutionary algorithms could get the global optimum solution for the multi-extreme value optimization problem. In the subdivision optimization or structure optimization methods for ship, the population-based methods are widely used in the existing literature, such as genetic algorithm (Chen et al., 2010; Olcer et al., 2006; Papanikolaou et al., 2010; Vasoncellos, 2010; Turkmen and Turan, 2007), and particle swarm optimization (Cui and Turan, 2010) etc. However, for the problem that has numerous extreme values, SISOM for example, it is very difficult for the population-based methods to avoid the premature convergence problem. GA has been used to solve optimization model (1) in this study initially, but it proved to be low in rate and the optimum solutions are closely related to the random initial populations. So in this paper, the gradient-based algorithm is used to solve optimization model (1). Although gradient-based algorithm could not necessarily converge to the gloal optimum solution, it converges to the one that closed to the original ISP, and it is also very valuable to engineering practice.

In optimization model (1), constraint a and constraint b is associated to buoyancy function $B(x,\mathbf{A})$, which is related to the hull surface, a 3D irregular surface with complex mathematical expression. As the floatation of the ship is changing in the optimization process, it is very difficult to solve optimization model (1) with such complex constraints directly for gradient-based algorithm. In order to simplify the constraints, merge constraint a and b into the objective function, which means the objective function is changed and a and b is removed from the constraints of model (1). Then the new objective function is the maximum SWBM on premise that the gravity-buoyancy balance equation as well as the gravity-buoyancy moment balance equation is established. After that, the new objective function becomes:

$$g(\mathbf{A}) = \max\left(f(x) = \left| \int_a^x \int_a^y B(t,\mathbf{A}) - LW(t) - DWT(t)dtdy \right| \right) \tag{2}$$

where, $\begin{cases} \int_a^f \left(B(x,\mathbf{A})\right) - LW(x) - DWT(x)dx = 0 \\ \int_a^f \left(B(x,\mathbf{A}) - LW(x) - DWT(x)\right)xdx = 0 \end{cases}$

The above modification simplifies the constraints, but makes the objective function more complex. However, it is not very important, for the complex objective function could be calculated through programming. After this modification, all the constraints could be expressed by algebraic expression with the variables. Then by means of penalty function method, optimization model (1) is converted into an unconstrained problem,

$$M(\mathbf{A}) = g(\mathbf{A}) + M_1 C(\mathbf{A}) + M_2 L(\mathbf{A}) + M_3 R(\mathbf{A}) \tag{3}$$

The meaning of the functions in Eq. (3) is as follows:

(1) $C(\mathbf{A})$ is the penalty item for CH volume, and it is used to make the optimum solution satisfy the capacity requirements of CHs and heavy CHs,

$$C(\mathbf{A}) = \left| \sum_{i=1}^{n-1} (A_i + A_{i+1}) \cdot (x_{i+1} - x_i) - C_c \right| + f \cdot \left| \sum_{i=1}^{\frac{n+1}{2}} V_{c2i} - C_h \right| \tag{4}$$

where coefficient $f = 1$ if the object ship has heavy cargo alternate loading condition, otherwise $f = 0$. Here, the volume and LCV of CH is calculated by integral of ISP section area along X coordinate

(2) $L(\mathbf{A})$ is the penalty item for LCV, and it is used to ensure that LCV for WBTs, CHs, and heavy CHs all satisfies the requirement. $L(\mathbf{A})$ is defined as:

$$L(\mathbf{A}) = s\left(x_b(A) - XB_{\max}\right) + s\left(XB_{\min} - x_b(\mathbf{A})\right) + s\left(x_c(\mathbf{A}) - XC_{\max}\right) +$$

$$s\left(XC_{\min} - x_c(\mathbf{A})\right) + f \cdot s\left(x_h(\mathbf{A}) - XH_{\max}\right) + f \cdot s\left(XH_{\min} - x_h(\mathbf{A})\right) \tag{5}$$

where coefficient f is the same as the one in function $C(\mathbf{A})$. $s(x)$ is signal function. $x_c(\mathbf{A})$, $x_b(\mathbf{A})$ and $x_h(\mathbf{A})$ is LCV penalty item for CHs, WBTs and heavy CHs respectively. $s(x)$ and the above LCV penalty items are defined as follows,

$$s(x) = \begin{cases} 0, x < 0 \\ x^2, x \ge 0 \end{cases} \tag{6}$$

$$x_b(\mathbf{A}) = \frac{\sum_1^{n-1} (2S_i - A_i - A_{i+1}) \cdot (X^2{}_{i+1} - X^2{}_i)}{2\sum_1^{n-1} (2S_i - A_i - A_{i+1}) \cdot (X_{i+1} - X_i)} \tag{7}$$

$$x_c(\mathbf{A}) = \frac{\sum_1^{n-1}(A_i + A_{i+1})\cdot(X^2{}_{i+1} - X^2{}_i)}{2\sum_1^{n-1}(A_i + A_{i+1})\cdot(x_{i+1} - x_i)} \tag{8}$$

$$x_h(\mathbf{A}) = \frac{\sum_{i=1}^{\frac{m+1}{2}} V_{c2i}\cdot X_{c2i}}{\sum_{i=1}^{\frac{m+1}{2}} V_{c2i}} \tag{9}$$

(3) $R(\mathbf{A})$ is the penalty item for variables' upper limit, and it is used to ensure that the section area of ISP at each corner position does not exceed the maximum one calculated according to pollution prevention and damage stability requirements. $R(\mathbf{A})$ is defined as follows:

$$R(\mathbf{A}) = \sum_1^n s(A_i - A_{i\max}) \tag{10}$$

In Eq. (3), M_1, M_2, M_3 are the penalty coefficients, and should be increased gradually with iteration time. The three coefficients at the k+1[th] iteration are calculated via:

$$M_i^{k+1} = cM_i^k \quad (1\le i\le 3) \tag{11}$$

where c>1 is the magnification coefficient, and it is specified according to experience. M_1^0, M_2^0, M_3^0 is the weight of the three penalty item. Generally, M_1^0 is set to1, M_2^0 and M_3^0 could be calculated with:

$$\begin{cases} M_2^0 = M_1^0\cdot Disp \\ M_3^0 = M_1^0\cdot Lpp \end{cases} \tag{12}$$

where *Disp* is the displacement of the ship under MMLC, and *Lpp* is the ship length between perpendiculars.

Suppose $Mcm\ (d, \varphi)$ is moment surface of the ship that indicates the relation between the righting moment with the trim φ and draft d. As to the regular transport ship, the partial derivative $\frac{\partial Mcm}{\partial d}$ and $\frac{\partial Mcm}{\partial \theta}$ exist and continuous approximately. So it can be proved that $\frac{\partial M_{\max M}}{\partial A_i}$ ($1\le i\le n$) exist and continuous, where M_{maxM} means the maximum SWBM. As a result, the gradient of $M(\mathbf{A})$ exists and is continuous in the domain approximately. On this base, the problem could be solved by the steepest descent method, and the k+1[th] solution could be calculated from the k[th] solution by the following equation,

$$\mathbf{A}^{k+1} = \mathbf{A}^k + \lambda\nabla M(\mathbf{A}^k) \tag{13}$$

where $\nabla M(\mathbf{A}^k)$ is the gradient of $M(\mathbf{A})$ at $\mathbf{A}^k$, λ>0 is the best step size. The initial ISP section areas are taken as the initial solution of iteration, $\mathbf{A}^0$. $M(\mathbf{A}^k)$ is closely related to the hull surface, which makes it impossible to express $\nabla M(\mathbf{A}^k)$ with mathematical expression. So difference method is used here to calculate the gradient of M,

$$\nabla M(\mathbf{A}^k) = \left(\frac{\partial M}{\partial A_1}, \frac{\partial M}{\partial A_2}, \ldots, \frac{\partial M}{\partial A_n}\right) \tag{14}$$

where the partial derivative of M with respect to A_i is calculated by means of centered difference,

$$\frac{\partial M}{\partial A_i} = \frac{M(A_i + \Delta A) - M(A_i - \Delta A)}{2\Delta A} \quad (1 \le i \le n) \tag{15}$$

$\nabla M(\mathbf{A}^k)$ is the steepest descent direction of $M(\mathbf{A})$ at $\mathbf{A}^k$. After the direction is obtained, the best step size λ, which makes $M(\mathbf{A})$ minimum at $\mathbf{A}^k$ along direction $\nabla M(\mathbf{A}^k)$ is required. The problem of calculating λ could be transformed into a single variable unconstrained optimization problem as follows:

$$\min \varphi(\lambda) = M\left(\mathbf{A}^k + \lambda \nabla M(\mathbf{A}^k)\right) \tag{16}$$

where $\mathbf{A}^k$ and $\nabla M(\mathbf{A}^k)$ are constant vectors. Dichotomy optimization method is used to solve Eq. (16), and λ is then calculated. After that, $\mathbf{A}^{k+1}$ is obtained by Eq. (13), and the next iteration begins. The convergence criterion for the iteration is

$$\left|\mathbf{A}^{k+1} - \mathbf{A}^k\right| < \varepsilon \tag{17}$$

where ε is the accurate error, $\varepsilon = 0.001$ is suggested for ships the DWT of which are between 20,000 *t* and 80,000 *t*. The optimization iteration continues until Eq. (17) is established, and then $\mathbf{A}^{k+1}$ is the optimum section areas of ISP at corner positions.

The solving process of SISOM is shown in Fig. 1. In the iteration process, if any of the constraint is not satisfied, the penalty function will increase the objective function. The three penalty coefficient increases along with the iteration time, which makes the solution feasible gradually. When all the requirements are satisfied, all the penalty items become zero, and then the optimazation direction is toward the one that makes the maximum SWBM minimum.

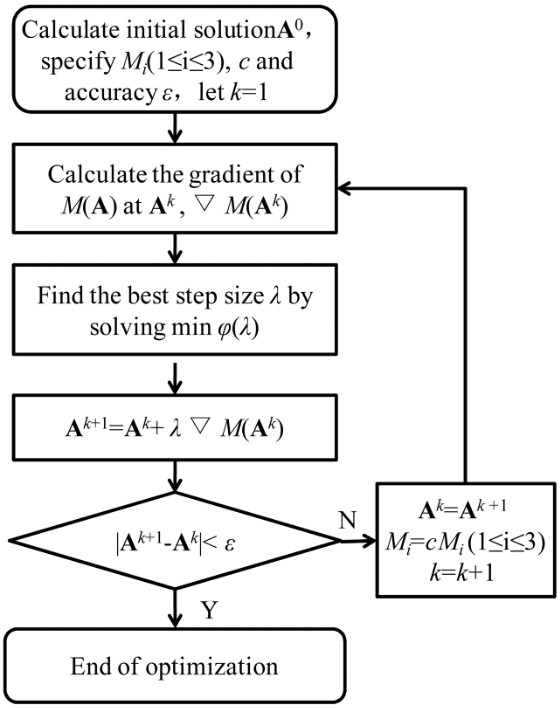

Fig. 1 Process of optimum solution for SISOM.

In this optimization model, coefficient *c* is important to convergence of the algorithm. If *c* is too small, then the algorithm will be low in convergence rate. If *c* is too large, the iteration may converge to an infeasible solution. According to the author's experience, the preferable range of *c* is [1.5, 4].

APPLICATION OF SISOM IN ENGINEERING PRACTICE

ISP shape optimization design for the 26,000 DWT product oil tanker

SISOM is applicable for most of the seagoing oil tanker and bulk carrier. Firstly, take a 26,000 DWT product oil tanker as example to discuss the application of SISOM in double shell oil tankers. The principal dimensions of the oil tanker are shown in Table 1.

Table 1 Principal dimensions of the 26,000 DWT product oil tanker.

Lpp, *m*	B, *m*	D, *m*	d, *m*	Disp, *t*	LW, *t*	LCG, *m*
164.00	27.40	14.50	9.50	35,300	8,600	70.60

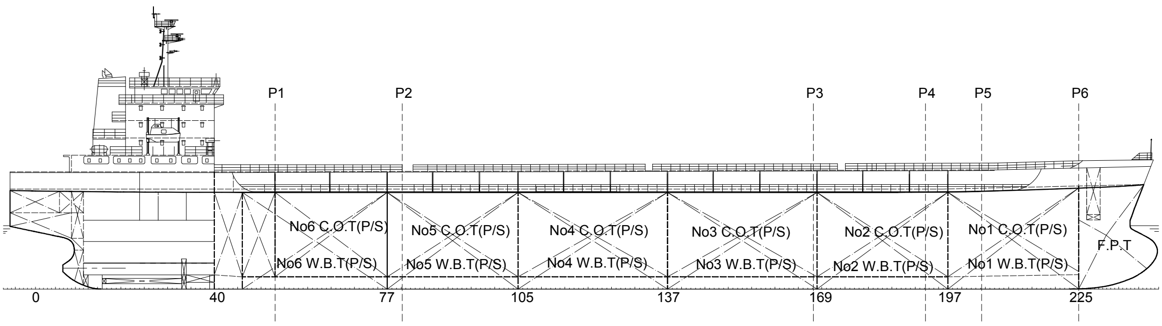

Fig. 2 Subdivision and corner position for the 26,000 DWT product oil tanker.

This oil tanker has six pairs of cargo oil tanks. Among all seagoing conditions, normal ballast departure condition has the maximum SWBM, as shown in Table 2. Therefore, the normal ballast departure condition is MMLC for this oil tanker. There are six corners, which are marked as P1 to P6 in Fig. 2, and the section area of ISP at each corner position is taken as variables.

The optimization converges after 24 iterations. The variables in each iteration step is shown in Fig. 3, which indicates that all variables change greatly in the first iteration, and return to the vicinity of the initial solution gradually in the following steps.

Table 2 The maximum SWBM of typical loading conditions for 26,000 DWT product oil tanker.

Loading condition	Ballast, Dep	Ballast, Arr	Full load	Light oil full load	Heavy oil alter load
Max. SWBM, *t.m*	81,028	72,026	-13,268	55,118	69,473

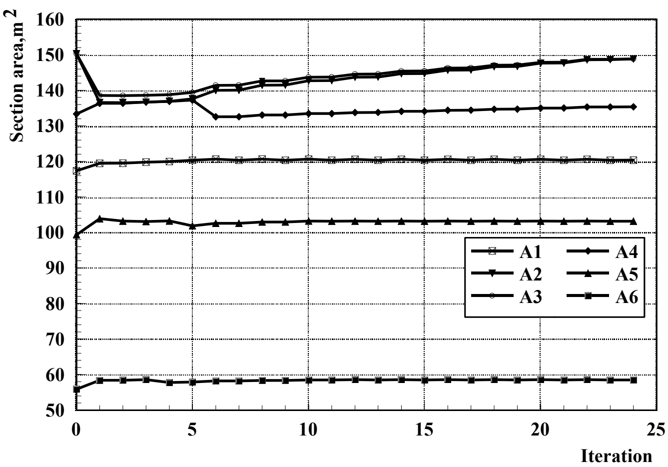

Fig. 3 The variables in iteration for 26,000 DWT product oil tanker.

The objective function $M(\mathbf{A})$ and the penalty items in each iteration step is shown in Fig. 4. In this instance, CH penalty item and the section area penalty item keeps zero in the whole iteration process.

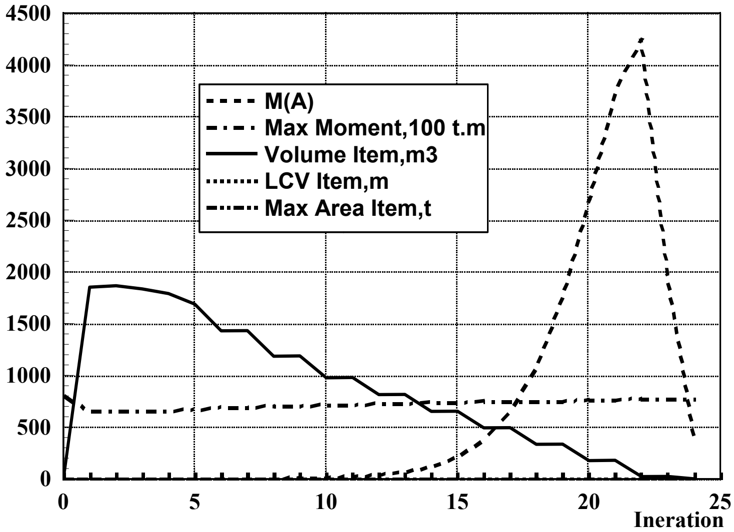

Fig. 4 Objective and penalty items in the iteration for 26,000 DWT product oil tanker.

Adjust ISP of the tanker according to its optimum section area. For this ship, ISP consists of three plates, which are the inner bottom, hopper tank sloping plate and double shell plate. Assume that double bottom height is the same as the initial ISP, double shell plate is perpendicular to base plane, and the angle of hopper tank sloping plate in the transverse section keeps unchanged. Besides, suppose that area variation of each section distributes equally in order to minimize the influence on the structure. Under these assumed conditions, the optimized ISP is created and shown in Fig. 5 compared with the initial one.

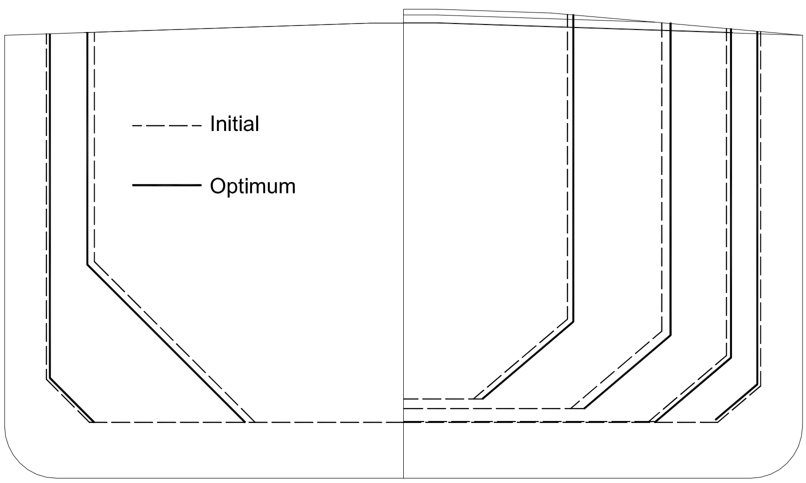

Fig. 5 Optimum ISP of the 26,000 DWT product oil tanker compared with the initial one.

The SWSF and SWBM curve before and after optimization is shown in Fig. 6. The maximum SWBM of the ship before optimum design is 81,028 *t.m*, and the one after optimization is 77,136 *t.m*. After optimization by SISOM, the maximum SWBM is reduced by 5%, and the maximum SWSF is reduced by 4% simultaneously.

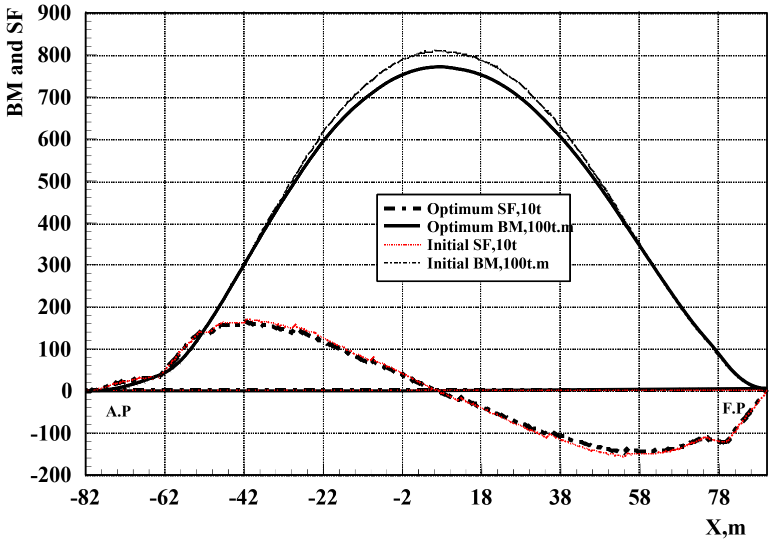

Fig. 6 SWSF and SWBM curves before and after optimization for the 26,000 DWT product oil tanker.

ISP shape optimization design for the 69,000 DWT bulk carrier

In this section, a 69,000 DWT single hull bulk carrier is taken as example to indicate the application of SISOM in seagoing bulk carriers. The subdivision drawing of the bulk carrier is shown in Fig. 7, and the principal dimensions of this ship are shown in Table 3.

Table 3 Principal dimensions for the 69,000 DWT bulk carrier.

Lpp, *m*	B, *m*	D, *m*	d, *m*	Disp, *t*	LW, *t*	LCG, *m*
217.00	32.26	18.30	13.20	78,700	9,220	119.76

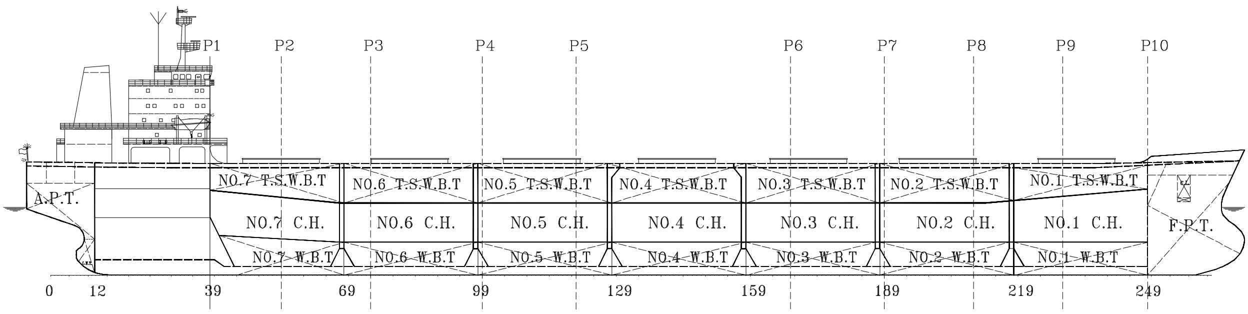

Fig. 7 Subdivision and corner position for the 69,000 DWT bulk carrier.

This bulk carrier has 7 CHs and 17 pairs of water WBTs in CH segment. ISP has 10 corners as shown in Fig. 7, and the section areas of ISP at these 10 corner positions are taken as variables. The maximum SWBM of typical loading conditions of this ship is shown in Table 4.

Table 4 The maximum SWBM of typical loading conditions for the 69,000 DWT bulk carrier.

Loading condition	Normal ballast	Heavy ballast	Full load	Heavy cargo alter. load
Max. SWBM, *t.m*	103,116	95,240	-24,772	128,160

The loading condition with maximum SWBM is the heavy cargo alternate loading condition for this bulk carrier, and this loading condition is made MMLC. The variation curves for each variable are shown in Fig. 8. The optimization complete after 12 iterations.

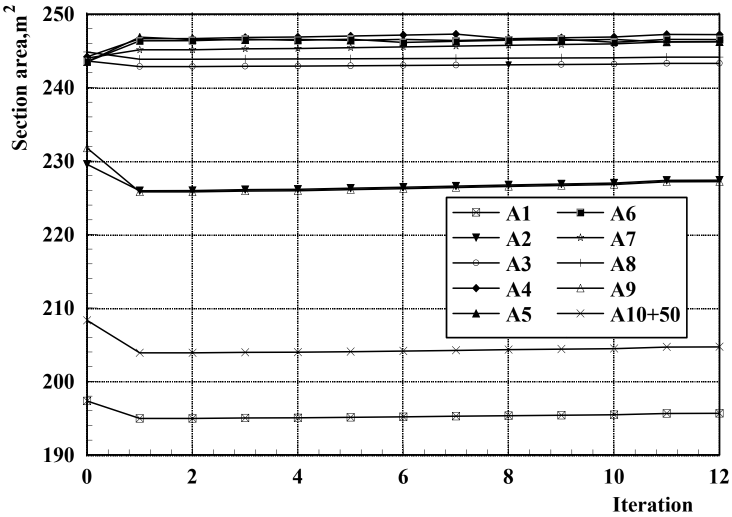

Fig. 8 Variables in the optimization iteration for the 69,000 DWT bulk carrier.

The variation curves for objective function $M(\mathbf{A})$ and penalty items are shown in Fig. 9. In the last iteration step, all the penalty items are zero, which means all the constraints are satisfied in the final solution. So the optimum solution is feasible.

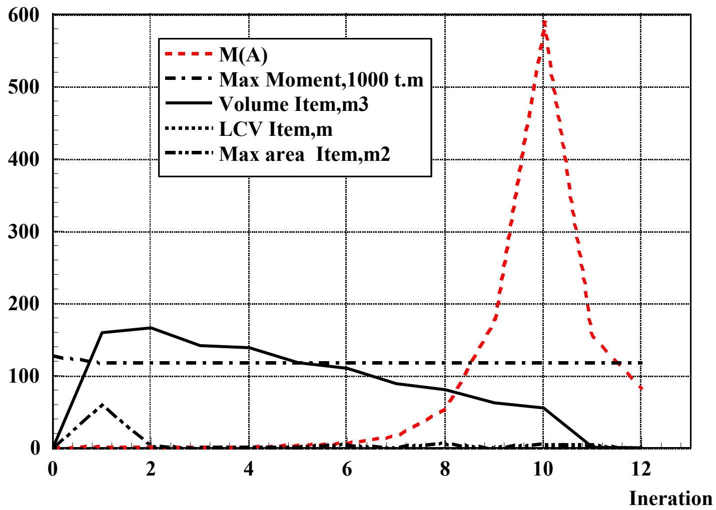

Fig. 9 Objective and penalty items in the iteration for the 69,000 DWT bulk carrier.

This ship is a single hull bulk carrier, so the variation for the transverse section area of ISP consists of two parts, the hopper tank variation and the topside wing tank variation. Suppose that the double bottom height is not to be changed, and then the variation of hopper tank is caused by offsetting of the Hopper Tank Sloping Plate (HTSP) along the normal of itself, and the variation of topside wing tank by that of the Topside Wing tank Sloping Plate (TWSP). In order to avoid influencing the structure too much, ISP variation is made uniform distribution in HTSP and TWSP. For ISP section corresponding to the i^{th} variables, HTSP offset d_{Hi} and the TWSP offset d_{Wi} is calculated by the following equation:

$$\begin{cases} d_{Hi} = \dfrac{dA_i \cdot L_{Hi}}{L_{Hi} + L_{Wi}}, \\ d_{Wi} = \dfrac{dA_i \cdot L_{Wi}}{L_{Hi} + L_{Wi}} \end{cases} \quad (1 \le i \le n) \tag{18}$$

where d_{Ai} is the difference of the i^{th} optimum section area with the initial one. n is the section number, 10 for this instance. L_{Wi} and L_{Hi} are the length of TWSP and HTSP of the initial ISP for the i^{th} section. Adjust ISP with Eq. (18), and the optimized ISP by SISOM is shown in Fig. 10 together with the initial one of this bulk carrier.

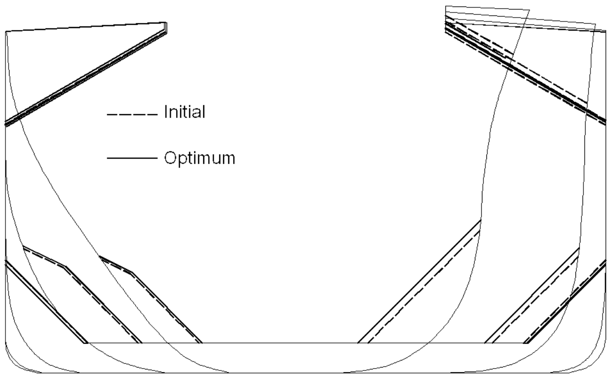

Fig. 10 Optimum ISP of 69,000 DWT bulk carrier compared with the initial one.

The SWSF and SWBM curves before and after optimization for this bulk carrier is shown in Fig. 11. For the initial design scheme, the maximum SWBM is 128,160 *t.m*, and the maximum SWSF is 5,280 *t*. After optimization with SISOM, the maximum SWBM is 119,223 *t.m*, and the optimized maximum SWSF is 5,083 *t*. The maximum SWBM and the maximum SWSF is reduced by 7% and 4% respectively with SISOM.

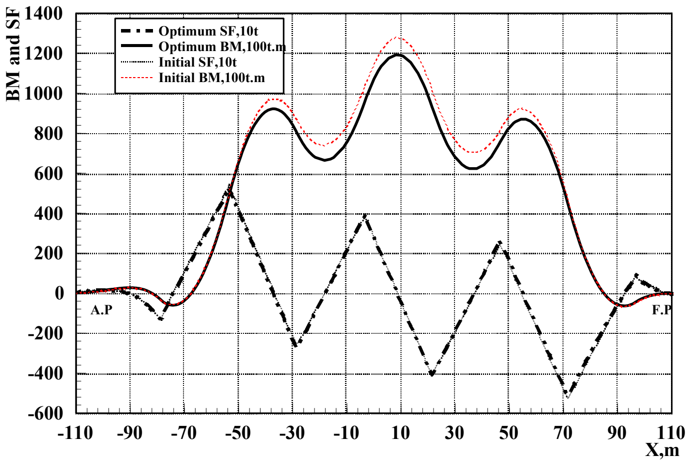

Fig. 11 SWSF and SWBM curves before and after optimization for 69,000 DWT bulk carrier.

Optimization result analysis

In the first application, SISOM reduced the maximum SWBM of the oil tanker by 5%. For this oil tanker, SWBM occupies 42% of the total bending moment. So SISOM is able to decrease the maximum bending stress by 2%, which will greatly reduce the risk of structural yield and buckling failure under extreme sea conditions, and this is especially important to the ship that has been used more than 10 years. For most of the transport ship, the hull should undergo the full loaded and ballast condition in sequence, and hull girder bears large sagging and hogging moment alternatively. This is an important cause of structure fatigue failure. SISOM is able to decrease the maximum SWBM of hull, which is equivalent to reduce the amplitude of the alternating load. So SISOM is an efficient way to improve the hull structure fatigue strength. The application to the bulk carrier has the similar conclusion with the oil tanker. Moreover, SISOM is also an effective method for ship optimization design. As SISOM is able to reduce the requirement of hull section modulus according to the rules such as JTP (2006) and JBP (2006), the thickness of some longitudinal plates could be reduced according to the optimum solution, and the deadweight of the ship is increased as a result. For example, according to the optimization result of the 69,000 DWT bulk carrier, the deck plate could be reduced by 1.5 *mm* in the range of CH segment, which means the total steel weight of the ship could be decreased by 0.4%. That is beneficial to deducing construction cost and improving the ship loading capacity.

CONCLUSIONS

In this paper, a new method named SISOM is proposed to improve the safety of seagoing transport ship via decreasing the maximum SWBM under all typical loading conditions. Being different from the existing methods, SISOM decreases the maximum SWBM by a novel way. The shape of ISP is taken as optimization object in SISOM, and the maximum SWBM of ship could be decreased effectively by optimizing the shape of ISP slightly. In order to ensure the optimized solution feasible, the main performance parameters of ship, which may be changed in the optimization process, are taken as constraints in the optimization model, and the optimum solution satisfies the following design requirements:

(1) Loading capacity requirement.
(2) Propeller and rudder immersion requirement.
(3) Minimum requirement of the fore end wave slap.
(4) Bridge visibility requirement.
(5) Floatation under typical loading conditions.
(6) Minimum requirement of pollution prevention and damage stability.
(7) Requirement of design and construction productivity, such as all plates in ISP are planer, transverse sections in the range of parallel middle body are the same.

SISOM is suitable for seagoing transport ship such as oil tanker and bulk carrier. The two applications presented in this paper prove that SISOM has good convergence and high efficiency. SISOM could effectively decrease the maximum SWBM by modifying ISP shape slightly, on promise that the optimum solution meet the requirements of main performances of ship, and that productivity in design and construction stage will not be affected too much. In conclusion, SISOM is a practical engineering approach with high efficiency, by which the safety of the seagoing transport ship could be improved effectively.

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