Ship compartment modeling based on a non-manifold polyhedron modeling kernel

Sang-Uk Lee a,1, Myung-II Roh b,*, Ju-Hwan Cha c,2, Kyu-Yeul Lee d,3

a EzGRAPH Co. Ltd., Yoksam1-Dong, Seoul 135-909, Republic of Korea
b School of Naval Architecture and Ocean Engineering, University of Ulsan, Mugeo-Dong, Ulsan 680-749, Republic of Korea
c Department of the Naval Architecture and Ocean Engineering, Seoul National University, Shinlim-Dong, Seoul 151-742, Republic of Korea
d Department of the Naval Architecture and Ocean Engineering, and Research Institute of Marine Systems Engineering, Seoul National University, Shinlim-Dong, Seoul 151-742, Republic of Korea

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Abstract

Currently, ship compartment modeling systems which are being used in shipyards support compartment modeling of the bottom-up approach. That is, a compartment model of a ship is being generated by modeling all compartments one by one. However, this method requires much time and efforts because the ship consists of compartments of several tens to several hundreds. To solve this problem, a new compartment modeling method of the top-down approach is proposed in this study. The proposed method is based on space subdivision as if we cut food into many small pieces. For this, a new modeling operation named a “Place” operation which is a kind of Boolean operations is developed. A non-manifold polyhedron modeling kernel containing the Place operation is also developed. Furthermore, a ship compartment modeling system was developed based on the modeling kernel. To evaluate the applicability of the proposed method and the developed kernel, it is applied to compartment modeling of various ships. As a result, it is shown that a designer can perform easily and rapidly compartment modeling by using the proposed method in early time.

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1. Introduction

1.1. Background of this study

A ship consists of one hull form and a number of compartments. Here, the hull form represents an outer part which touches fresh or sea water. Hull form modeling is the task that makes the hull form have a streamline shape. We call an output of hull form modeling a hull form model.

On the other hand, the compartments represent spaces to load various cargos. In the case of a bulk carrier which is an ocean-going vessel used to transport bulk cargo items such as ore or food staples (rice, grain, etc.) and similar cargo, the number of compartments amounts to about 100–200, and in the case of a VLCC (Very Large Crude oil Carrier) which an ocean-going vessel used to transport liquids such as oil, the number of compartments amounts to about 50–100. Compartment modeling is the task that subdivides the hull form into a number of compartments with satisfying ship owner’s requirements, international rules, and regulations. We call an output of compartment modeling a compartment model. Fig. 1 shows the hull form model and the compartment model of a deadweight 300,000 ton VLCC (hereafter simply referred to as the ‘300K VLCC’) which can load the crude oil of the weight of 300,000 ton in its compartments.
Compartment modeling is performed at the initial stage of ship design. For this task, a designer uses a CAD system called a ship compartment modeling system, hereafter simply referred to as the ‘compartment modeling system’, such as SIKOB, NAPA, TRIBON Initial Design, etc. All compartment modeling systems have their own compartment modeling methods. However, these methods are based on the bottom-up approach for compartment modeling. That is, a compartment model of the ship is being generated by modeling all compartments one by one. Thus, these methods require much time and efforts because the ship consists of compartments of several tens to several hundreds. Furthermore, it is a critical problem because compartment modeling must be performed as soon as possible at the initial design stage. To solve this problem, a new compartment modeling method of the top-down approach was proposed in this study. The proposed method is based on space subdivision as if we cut food into many small pieces. Using the proposed method, a compartment model can be generated by subdividing a hull form model with arbitrary planes such as bulkheads. Here, a bulkhead means a type of a partition which exists between adjacent compartments. In addition, a non-manifold polyhedron modeling kernel was also developed. The developed kernel has a suitable data structure required for representing the intermediate and final shapes of the compartment model, and a suitable modeling function required for implementing the proposed method. Furthermore, a ship compartment modeling system was developed based on the modeling kernel. To evaluate the applicability of the proposed method and the developed kernel, it was applied to compartment modeling of various ships.

1.2. State of the arts

Currently, commercial compartment modeling systems being widely used in shipyards are as follows: SIKOB, NAPA, and TRIBON Initial Design.

SIKOB [1], which is being widely used in many shipbuilding companies, cannot represent efficiently the internal shape of compartments of a ship on display. That is, it is hard for a designer to define and verify the compartments, because the system only supports the text file-based input method and is poor in display function of the compartments, as shown in Fig. 2. Also, the designer should know the shape of the compartments beforehand, and it is hard to transmit the information of the compartments to following design stages such as the detailed and production design stages.

In the case of NAPA [2] and TRIBON Initial Design [3], one compartment is defined by six surfaces surrounding the corresponding compartment, as shown in Fig. 3. These six surfaces are generally obtained by performing the surface-surface intersection with a hull form model. However, this modeling method has the problems that a bulkhead is...
redundantly defined between adjacent compartments, as shown in Fig. 3, and it requires much time and efforts.

Compartment modeling methods, that is, generation methods of the compartment model at the initial design stage have been the focus of studies in practical engineering fields as well as academic fields. Park et al. [4] developed a GUI (Graphic User Interface) system based on SIKOB. The developed system had some user-friendly functions such as a function for defining sections of compartments using GUls, a function for roughly visualizing the compartments, etc. However, the developed system could not overcome inherent limitations of SIKOB because it is based on SIKOB.

Academic researches related to the generation of the compartment model have been studied as well. Park and Lee [5] developed a ship compartment modeling system which is similar to SIKOB. The developed system had better functions, such as a function for defining sections of compartments from a hull form model, a function for roughly visualizing the compartments, etc., than those of SIKOB. However, a compartment modeling method of the developed system was similar to that of SIKOB and did not support GUls for defining the compartments. Kang and Lee [6] proposed a compartment modeling method in which compartments are defined using the intersection calculation between a hull form model and an infinite plane. However, the proposed method could generate only compartments having a convex shape and it is hard to generate compartments having a concave shape although some compartments of a ship have a concave shape.

Many of the systems and researches that have been performed have limitations, as mentioned above. To overcome these limitations, we developed a new method for rapidly generating the compartment model from the hull form model and evaluated the applicability of the proposed method.

The remainder of this paper is as follows. Section 2 describes the proposed method for compartment modeling. Section 3 describes the developed kernel to efficiently represent the compartment model. Section 4 describes the developed modeling function for rapidly generating the compartment model. Section 5 presents application examples of the proposed method and the developed kernel. Finally, Section 6 presents a summary of this study.

2. Proposal of a new compartment modeling method

Fig. 4 shows the proposed method for compartment modeling based on space subdivision in this study. The essence of the proposed method is to define a source of a bulkhead and to subdivide selected target spaces (compartments) by inserting the source of a bulkhead in order to generate a more detailed compartment model. By repeating this top-down modeling process, a designer can generate the final compartment model from the initial, simple model. Using this method, the designers can perform compartment modeling in the intuitive way that he defines primary bulkheads and subdivides one large compartment into several small compartments, and then defines secondary bulkheads and subdivides former resultant compartments into smaller ones without imaging the final shape of each compartment. Fig. 4 shows the method of subdividing the large compartment ‘B’ into two small compartments ‘B’ and ‘C’ by inserting the source of a bulkhead into ‘B’.

Fig. 5 shows an example of applying the proposed method based on space subdivision to compartment modeling of a 300K VLCC. In step (a), a box including a whole hull form has been defined. Through steps (b) and (c), the box is subdivided into three large compartments: aft tank, cargo tank, and fore tank. Then, in step (d), the cargo tank is again subdivided into one center cargo tank, two side cargo tanks, and one ballast tank. Afterward, several trans-
verse bulkheads are inserted at proper locations in order to make many compartments simultaneously. As a result, a subdivision model is generated as shown in Fig. 5i. In the last step (j), the final compartment model is generated by inserting a hull form as a bulkhead into the subdivision model and deleting all the compartments that are outside...
of the hull form. To support this type of modeling, a script file-based user interface and GUIs were developed to get input from a designer.

3. Development of a non-manifold polyhedron modeling kernel

Two components are basically required to generate a complicated shape like a compartment model. One is a data structure that can represent effectively various shapes and the other is modeling functions that can create, modify, and delete elements of the data structure in order to generate the wanted shape. A software module including these two components is called a geometry modeling kernel.

The geometry modeling kernel has been evolved in sequence of a wireframe modeling kernel, a surface modeling kernel, a solid modeling kernel [7], and a non-manifold modeling kernel according to the characteristics of geometry representation. In this study, a non-manifold modeling kernel was developed for representing the compartment model and for implementing its modeling method.

3.1. Non-manifold model

A non-manifold model is the model that has been studied in the field of geometry modeling in recent years. This model can represent the opened shape of which a boundary edge belongs to only one face or the shape of which one edge is shared by more than two faces as well as various shapes which can be represented by a wireframe model, a surface model, and a solid model. On the other hand, a solid model can represent only the closed shape of which every edge should be shared by two faces. Fig. 6 shows a comparison between the solid model and the non-manifold model. As shown in this figure, the non-manifold model is effective to represent various models of a ship such as a hull form model, a compartment model, and a hull structural model.

3.2. Polyhedron

A polyhedron is the shape of which all faces are planar and thus all edges are linear. If all shapes are polyhedra, the calculation speed of intersection operations between the polyhedra greatly increases because all intersection operations can be performed by plane–plane intersections. Furthermore, the fast, exact calculation of volume properties of the polyhedra such as the volume and the center of gravity is possible using the characteristics of the polyhedron. Finally, the implementation of a geometry modeling kernel supporting the polyhedron is easier than that supporting a free shape, and the robustness of many modeling operations including the intersection operations of the geometry modeling kernel can be improved.

3.3. Non-manifold polyhedron modeling kernel

In this study, a non-manifold polyhedron modeling kernel of which a target shape for many modeling operations is restricted to a non-manifold polyhedron shape was developed based on many Refs. [8–11]. However, a data
structure of the developed kernel can represent a free shape with curved surfaces because a hull form of a ship consists of many curved surface patches. Before being used in compartment modeling, the hull form is converted into a polyhedron using a triangular mesh generation method. Fig. 7 shows the configuration of the non-manifold polyhedron modeling kernel developed in this study. As shown in this figure, the developed kernel consists of a non-manifold data structure, Euler operations, Boolean operations, and a Place operation.

The non-manifold data structure is a data structure intended to efficiently represent a non-manifold model by representing hierarchically the relationship between topological entities such as a vertex, an edge, a face, a region, and so on. That is, this data structure is a container to save geometric and topological information of the non-manifold model. This data structure consists of many classes such as a vertex class, an edge class, a face class, a region class, and a class for the adjacent information among these entities. Fig. 8 shows the non-manifold data structure of the developed kernel.

The Euler operations are tools for generating or modifying the non-manifold data structure. That is, the Euler operations are a set of low level operations that modify the non-manifold model with satisfying Euler’s formula for non-manifold geometry. Here, Euler’s formula represents the relation of the numbers of vertices, edges, faces, regions, and so on. Fig. 9 shows the Euler operations of the developed kernel.

The Boolean operations are tools for easily and compactly generating the non-manifold model. That is, the Boolean operations are several high level operations which are essential to generate a complicated shape from simple shapes using the concept of set operations of union, inter-
section, and subtraction (or difference). Fig. 10 shows the Boolean operations of the developed kernel.

Lastly, the Place operation is a newly developed operation in this study. This operation supports an efficient ship compartment modeling based on space subdivision. It has been implemented by extending Boolean operations. More details about this operation will be explained in the next section.

4. Development of a Place operation for efficient ship compartment modeling

4.1. Boolean operations

In the field of geometry modeling, Boolean operations are set operations to generate a new model from two models by treating the models as sets of three dimensional points. There are three types of the Boolean operations: union, intersection, and subtraction. The Boolean operations are very powerful modeling methods to generate a complicated shape from the union, intersection, or subtraction of two and more simple shapes.

In general, the Boolean operations for a non-manifold model are implemented using the concept of ‘Merging and Selection’ in many studies [8–11], as shown in Fig. 11. The implementation of the Boolean operations consists of three steps. In the first step named a merging step (Fig. 11a), a merged set is generated by merging a model ‘A’ with a model ‘B’. For this, intersected elements such as vertices and edges are generated by the intersection calculation between all elements (vertices, edges, and faces) of the model ‘A’ and those of the model ‘B’. Then, a merged set is generated by merging the model ‘B’ with the model ‘A’ including the intersected elements. In the second step named a selection step (Fig. 11b), some elements of the merged set are marked as live elements according to a selection condition such as the union, intersection, and subtraction. In the final step named a flush step (Fig. 11c), the final model of the Boolean operations is generated by deleting non-marked elements from the merged set.
4.2. Place operation for ship compartment modeling

A compartment model of a ship can be generated using the Boolean operations. That is, it is possible to implement a new method for compartment modeling using the combination of the Boolean operations. However, to implement it by such a way is inefficient as you can see below. Therefore, a new operation for compartment modeling, named a ‘Place’ operation, was developed by modifying some parts of the algorithm for the conventional Boolean operations in this study. Fig. 12 shows the concept of the Place operation developed in this study. As shown in this figure, the Place operation, ‘Place B at A’, is the operation to subdivide a model ‘A’ with a model ‘B’. That is, it extracts the boundary of the model ‘B’ which exists in the model ‘A’ from the model ‘B’ and merges it into the model ‘A’. As a result, the model ‘A’ is subdivided into two regions.

In this study, the Place operation was implemented by modifying the merging step (Fig. 11a) of the conventional

![Fig. 11. Implementation of the Boolean operations for the non-manifold model using the concept of ‘Merging and Selection’.

![Fig. 12. Concept of the Place operation developed in this study.

![Fig. 13. Overall process of the Place operation for a simple compartment model.

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Boolean operations with the selective intersection and merging. Fig. 13 shows overall process of the Place operation for a simple compartment model. In Fig. 13a, a model ‘A’ represents a compartment model subdivided into two compartments: ‘R1’ and ‘R2’. A model ‘B’ represents a bulkhead. Here, a bulkhead means a type of a partition which exists between adjacent compartments. We suppose that we subdivide the compartment ‘R1’ of the model ‘A’ into two small compartments. In the first step (Fig. 13b), the compartment ‘R1’ is designated to the target compartment for the Place operation. Then, only the elements of this compartment, not the whole elements of the model ‘A’, are participated in the intersection calculation with the model ‘B’. This process is called a ‘selective intersection’. As a result, the resultant intersection elements are added in the models ‘A’ and ‘B’. In the second step (Fig. 13c), the elements of the model ‘B’ which belong to the target compartment are searched and merged with the model ‘A’. As a result, a merged set shown in Fig. 13c is generated. This process is called a ‘selective merging’. These two steps correspond to the merging step (Fig. 11a) of the conventional Boolean operations. The merged set equals to the final compartment model having three compartments: ‘R1’, ‘R2’, and ‘R3’, as shown in Fig. 13d. Like this, in the case of the Place operation, the selection step (Fig. 11b) and the flush step (Fig. 11c) of the conventional Boolean operations are not required because of the introduction of the ‘selective intersection and merging’. That is, all the elements of the merged set are marked as live elements and no element is supposed to delete.

Let us implement the Place operation with the conventional Boolean operations described in Section 4.1. Fig. 14 shows overall process of the conventional Boolean operations for a simple compartment model. In the first

Fig. 14. Overall process of the conventional Boolean operations for a simple compartment model.

(a) Definition of a source of a lower stool

(b) Execution of the Place operation

Fig. 15. Example of defining a lower stool in the cargo hold of the 40K PC.
step (Fig. 14a), the Boolean intersection operation is performed between the models ‘A’ and ‘B’ in order to generate the model ‘B’ fitted with the model ‘A’. In the case of the Boolean operations, the target model such as the models ‘A’ and ‘B’ is not some elements but a whole model. Thus, the resultant model of the Boolean intersection operation is a model ‘C’ having two faces, as shown in Fig. 14a. In the second step (Fig. 14b), the faces to be inserted in the compartment ‘R1’ is searched among all faces of the model ‘C’ and the other faces are deleted. As a result, a model ‘C’ is generated as shown in Fig. 14b. In the last step (Fig. 14c), the model ‘C’ is merged with the compartment ‘R1’. That
is, the Boolean union operation for the models ‘A’ and ‘C’ is performed in order to generate the final compartment model. As a result, the compartment ‘R1’ is subdivided into two compartments: ‘R1’ and ‘R3’.

If the overall process of the conventional Boolean operations are compared with that of the Place operation shown in Fig. 13, it can be seen that the Place operation is more efficient than the Boolean operations for compartment modeling because many elements merged and deleted in the case of the Boolean operations are not really merged in the case of the Place operation by applying the selective intersection and merging. Thus, the Place operation is more suitable for compartment modeling, as shown in Fig. 5 and it will raise the efficiency of whole work of compartment modeling.

5. Application to the deadweight 40,000 ton product carrier

The proposed method for compartment modeling was successfully verified by application in the generation of compartment models of various ships. This section presents portions of the verification process for a deadweight 40,000 ton product carrier (hereafter simply referred to as the ‘40K PC’). Figs. 15–17 show the modeling process of the 40K PC using the proposed method.

Fig. 15 represents an example of defining a lower stool in the cargo hold of the 40K PC. If a designer defines a source of the lower stool and performs the Place operation with the source of the lower stool (Fig. 15a), the lower stool is generated, as shown in Fig. 15b. That is, through the Place operation, the source of the lower stool is cut out by boundary faces of the cargo hold and the corresponding elements of the source which exist in the cargo hold are only inserted into the cargo hold. As a result, the final lower stool is generated, as shown in Fig. 15b. Similarly to this, Fig. 16 represents an example of defining an upper stool in the cargo hold. Moreover, Fig. 17 shows an example of defining a corrugated bulkhead which has a more complicated shape in the cargo hold. Like this, it is seen that the complicated compartments can be easily generated using the proposed method. Finally, Fig. 18 shows the final compartment model of the 40K PC using the proposed method. It took one designer about one hour to finish compartment modeling.

6. Conclusions and future works

In this study, a compartment modeling method based on space subdivision was proposed and a non-manifold polyhedron modeling kernel supporting the proposed method was also developed. Furthermore, a ship compartment modeling system was developed based on the modeling kernel. The developed modeling kernel consists of a non-manifold data structure, Euler operations, Boolean operations, and a Place operation. Here, the Place operation is a kind of the Boolean operations and newly developed operation for efficient compartment modeling in this study. To evaluate the applicability of the proposed method and the developed kernel, it was applied to compartment modeling of various ships such as VLCCs, bulk carriers, LNGCs (Liquefied Natural Gas Carriers), container ships, and so on. As a result, it was shown that a designer can perform easily and rapidly compartment modeling by using the proposed method.

As future works, it is required to develop various functions for ship hydrostatic calculation based on the fast, exact calculation of volume properties of the polyhedra such as the volume and the center of gravity. Moreover, it is required to improve the developed user interfaces and to implement interface functions with other systems such as a hull structural modeling system.

References

[1] SIKOB (currently, SEASAFE), <http://www.seasafe.com>