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Feature-based estimation of steel weight in shipbuilding

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ABSTRACT

An innovative and accurate method for estimating the steel weight and center of gravity (COG) of a ship in the preliminary design phase, named feature-based segment estimation (FSE), is presented. The method is based on principal component analysis (PCA) and includes corrections to capture ship features that are neglected by PCA. The feature analysis is based on three-dimensional (3D) computer-aided design (CAD) tools, which are used to build a framework of the ship components, deriving the general steel weight formulas and developing correction methods.

The method uses PCA to identify the principal parameters from a set of the ship's parameters and the main structural components, or segments, and to derive general equations for estimating the steel weight. Then, the estimated weight is adjusted using least squares regression based on the features of each structural segment. We demonstrate the practicality and effectiveness of the proposed method by applying 10 modern designs ranging from 1000 to 8500 twenty-foot equivalent units (TEU). The estimated results are presented and compared with those of the standard method, which consists of estimating the weight of the entire ship.

1. Introduction

1.1. Early stage steel weight and center of gravity estimation

Estimating the weight and center of gravity (COG) is an essential task in the design phase of a vessel. Accurate estimates are important for obtaining a light ship weight, and the quality of the estimate is crucial for the success of a project, affecting not only the ship design but also contract negotiations. The light ship weight estimate, which can be obtained using various methods, typically consists of the structural, outfit and machinery weights. However, the structural weight is the main factor in weight control because it has a significant influence on large merchant ships (Aasen and Bjorhovde, 2010; Watson, 2002). According to this research, the structural weight accounts for more than 70% of the total **light weight** of large container ships with a capacity of at least 8000 twenty-foot equivalent units (TEU) (CSBC Corporation, 2011). Although the structural weight in merchant ships includes all of the steel or other structural materials required for construction, including any filler metal in the welds, preliminary estimates typically include only the weight of the steel, which is obtained from a suitable empirical formula (Barrass, 2004) and then corrected for lesser items based on practice. Hence, we focus on methods that provide fast and accurate preliminary estimates of the steel weight.

From the beginning of the conceptual design to the contract stage, weight estimation is a challenging task if the new ship differs even slightly from previously built ships (Aasen and Bjorhovde, 2010). There are insufficient data to support accurate computations because a complete three-dimensional (3D) computer-aided design (CAD) model of the new ship is not available, and only an approximate arrangement plan exists. The lack of systematic empirical data, the limited project time and the considerable uncertainty of the results hinder the estimation task. However, the estimation results may be the deciding factor for success in winning a contract for designing or constructing the vessel. The estimate will affect the load capacity, speed, stability, seaworthiness, and delivery of the completed vessel, as well as the financial outcome of the project (Aasen and Bjorhovde, 2010).

Most estimation methods consider the weights of the hull and superstructure separately. There are 4 types of method. The first type is based on the ship's characteristics, where the weights are assumed to be functions of the main characteristics of the hull. Systematically varied container ship forms and sizes have been evaluated while considering the dimensional constraints, structure, form, speed, and propulsion (Bertram and Schneekluth, 1998). Many formulas have been derived with different constraints for container ships (Bertram and Schneekluth, 1998; Kerlen, 1985; Miller, 1968; Watson and Gilfillan, 1976). This type is also appropriate for optimization of the

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main dimensions (Kuniyasu, 1968; Lyon and Mistree, 1985; Nowacki, 2010).

The second type is based on data from existing ships. However, the data may be not satisfactory for the new types of ships. To obtain more precise estimates, the second method is typically combined with elements of the first method and appropriate regression analysis with data compiled from existing ships. This traditional estimation procedure is referred to as parametric estimation. An empirical formula in which indices are allotted to the ship's main dimensions, such as the length L, breadth B, depth D, and block coefficient (C_B), is used. Reference ship data are selected for use with the estimation formula and regression analysis (Watson, 2002). Two models of the regression-based parametric estimation, which use the cubic number $C_n = (L \times B \times D/100)$ or the area variable $L \times (B+D)$ as the independent variable, are more general in the early stages of design (Kazuhiko, 1998; Lamb, 2004). In addition, C_B may be an optional corrected parameter in these models. The models are still generally applied using commercial design software, such as Shipweight, Costfact, or Spar. The length of the superstructures and the ratio L/D can be used to correct the estimated result and then add the extra estimated weight (Benford, 1969). However, the parametric estimation method mainly uses overall ship parameters; it does not reflect local design features, such as a parallel midship section, the bow type, or the forecastle geometry. Most methods use fixed values or provide an empirical range for the coefficients of the main parameters. Therefore, the method provides only a rough estimate of the total weight and no estimate of the weight distribution. Although the method can be easily applied, choosing the appropriate formula and coefficients of the main parameters to precisely fit a ship design can be difficult in practice because of design changes. For example, a bulk carrier applying for the Common Structural Rules will have an increased hull weight (Zakki, 2013), but the hull weight can be reduced using high-strength steel (Løseth et al., 1994).

The third method is based on surfaces of the hull form. Due to the demand for faster and more efficient development of hull forms, designers face the challenge of quickly determining the hull form (Zhang et al., 2008). Because the method requires more information, including the thicknesses of the hull and the bulkheads for calculating the weight, it can be used when the general arrangement and the subdivisions are already approximately known.

The fourth method is based on the midship section modulus and is widely used by classification societies (AS, 2011). The weight and COG can be calculated by designing the scantlings of the midship section and estimating the weight distribution. Although CAD systems have emerged as powerful tools for calculating the structural limits and bending moments, human intervention is typically required to determine the midship section and weight distribution. For more precise estimates and to analyze the structure, the surface information and general arrangement used in the third method can be included using the CAD tools. If major changes are made to the design or a special configuration is used, the ship can be divided into sections that are considered separately. However, this process is slower, and it is difficult to respond quickly and flexibly to variations in requirements in the early design stage.

1.2. Feature-based method

In the field of computer-aided engineering (CAE), feature-based approaches collect features that are more important and meaningful modeling units than dots, lines, and faces by simplifying and reducing 3D CAD data (Kwon et al., 2015). In previous studies (Lee, 2005), geometric information was widely used as simplification criteria. Only a few conducted studies have considered non-geometric information. Sufficient design detail may rule out this approach in the earliest stages of design (Bole, 2007). A reasonable division of ships is a popular methodology in ship design. A segment framework is applied to analyze the parts of the structures of the ship (Son et al., 2011). The qualitative complexity criteria were considered for estimating six segments of a ship in the concept design stage (Caprace and Rigo, 2011). A feature-based cost model of ships for cost effectiveness measurements was developed based on the elementary parts of a ship's structure (Caprace and Rigo, 2012). In this study, we simplify the 3D CAD data of the built ships under the specific segment framework of ships to analyze and mine the features of weight that are not only geometric. Then, the features of the relationships between these hull segments are considered and applied to estimate the weight and to correct the results of the segment estimations.

1.3. Related research

The proposed method uses the configuration segment concept and principal component analysis (PCA) to build segment frameworks and thereby obtain estimates for parts of the ship in addition to the entire ship, regardless of the differences between the new design and previous designs. The segment concept originates from the research of Son et al., which established a preliminary cost estimation method for ships using the bill of materials (BOM), 3D computer-aided manufacturing (CAM) tools and a computerized expert-system approach. Rather than computing an estimate for the entire ship, the method computes estimates for each configuration segment, which can be duplicated from similar parts of previously built ships (Son et al., 2011).

PCA, a multivariate analysis method, is used as the basis of the method to enable the accommodation of completely new designs. The earliest descriptions of PCA were given by Pearson (1901) and Hotelling (1933) and were subsequently combined by Atchley and Bryant (1975). In many physical and statistical investigations, it is desirable to represent a system of points in a plane or a higher dimensioned space using the “best-fitting” straight line or plane. Analytically this consists of taking $y = a_0 + a_1x_1 + a_2x_2 + \ldots + a_nx_n$, where $y, x_1, x_2, \ldots, x_n$ are variables, and determining the “best” values for the constants $a_0, a_1, a_2, \ldots, a_n$ in relation to the observed corresponding values of the variables. Pearson was concerned with finding lines and planes that best fit a set of points in n-dimensional space, and the geometric optimization problems that he considered led to principal components (PCs). PCA can use an orthogonal transformation that is determined by the eigenvector and eigenvalues to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called PCs. This transformation is defined in such a way that the first PC has the largest possible variance and each succeeding component in turn has the highest variance possible under the constraint that it be orthogonal to the preceding components.

Pearson's comments regarding the computations, given over 50 years before the widespread availability of computers, are interesting. He stated that his methods can be easily applied to numerical problems of four or more variables (Jolliffe, 2002). In this study, his observations are true in the domain of the ship weight estimation. PCA can also be used to identify the most important factors among a set of parameters. We follow the approach of Hart et al. (2012), who applied PCA to identify the physical parameters of ships with the highest correlations to the cost. However, we propose new parameters that are relevant to the weight of the structure.

Aasen et al. proposed a system for estimating weights and the COG early in the design stage through the use of parametric estimation formulas obtained from regression analysis of historical