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A decision support system for mission-based ship routing considering multiple performance criteria

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ABSTRACT

It is crucial to evaluate the risk associated with marine vessels subjected to inclement weather and sea conditions when developing a decision support system for ship routing. The generalized decision making framework developed in this paper performs a variety of tasks, including, but not limited to quantifying the flexural and fatigue performance of ship structures and employing multi-attribute utility theory to evaluate ship mission performance. A structural reliability approach is utilized to compute the probability of failure considering the uncertainties in structural capacity and load effects; specifically, effects of flexural and fatigue damage are investigated. The expected repair cost, cumulative fatigue damage, total travel time, and carbon dioxide emissions associated with ship routing are considered as consequences within the risk assessment procedure adopted in this paper. Additionally, the decision maker's risk attitude is integrated into the presented approach by employing utility theory. The presented methodology can assist decision makers in making informed decisions concerning ship routing. In order to illustrate its capabilities the approach is applied to the Joint High-speed Sealift Ship.

1. Introduction

When a ship is deployed on a given mission, the route the vessel traverses is typically a predetermined path with known potential sea conditions (e.g., sea states). Thus, a decision maker must determine, before the mission, which route a ship may take. It is crucial to evaluate the risk associated with marine vessels subjected to inclement weather and sea conditions when developing a decision management system for ship routing. Ship mission routing can be established considering the strength of the hull, accounting for both flexural and fatigue damage. Additionally, a multi-attribute decision making process may be incorporated to form a robust framework for ship routing that accounts for a wide range of consequences (e.g., total travel time and repair loss). The uncertainties associated with the risk evaluation process must also be included within a generalized ship routing decision making framework. During a mission, a ship must always satisfy safety and serviceability requirements. In some cases, marine vessels are forced to follow certain routes while simultaneously handling time and distance constraints; this combination of dire conditions puts ships in danger of accruing damage that may negatively impact society and the surrounding environment. Ultimately, ship mission performance assessment is of vital importance for ship managers since it provides them guidance for the real-time decision making.

Often, marine vessels are used beyond their intended design life and are, therefore, found under-performing in terms of mission reliability. Consequently, it is of the utmost importance to assess the safety of ship structures by employing a holistic management program to ensure their functionality considering both flexural failure and fatigue damage. Ship performance associated with ultimate flexural failure of the hull's mid-ship section is considered as one of the most critical criteria regarding mission safety assessment [8]. Although the reliability of ship structures considering flexural failure has been previously studied [2,4,9,46,53,54], fatigue failure has yet to be comprehensively examined in a marine vessel routing context. Moreover, since ship structures are continuously subjected to oscillatory environmental loads, the risk associated with fatigue damage under the loading cases must be carefully considered [24,36]. The evaluation of fatigue damage associated with a ship's midsection is integral to ship routing performance assessment [40]. Overall, the failure associated with both hull girder collapse and fatigue damage must be considered simultaneously in order to capture the true performance of a marine vessel.

The spectral-based fatigue method is widely used in the fatigue damage evaluation of marine structures. In practice, the fatigue damage analysis of ship structures is often treated as a linear process and assessed using the spectral method [1,12,30]. Fatigue damage

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assessment may be implemented by utilizing a linear model to compute the response of a ship under wave loading [42]. The linear assumption ultimately allows for the solution of the hydrodynamic problem to be represented in the frequency domain. Several previous research efforts have investigated the role of the wave-induced vertical bending moment in the spectral fatigue analysis of marine vessels [35,40,42]. Furthermore, the combined effects of both the vertical and horizontal hull girder bending moments were considered in the fatigue damage assessment by Wang [58] and Xue et al. [59]. Additionally, the cumulative fatigue damage associated with a ship structure prior to and during a mission should be considered within the proposed framework. Since existing ship structures already have accumulated some fatigue damage, they may not be able to handle additional damage, especially if they are at late stages within their lifetimes. Accordingly, it is the decision maker's responsibility to determine whether a ship can still embark on a mission considering the cumulative fatigue damage.

The emissions associated with an operating marine vessel are regulated by the International Maritime Organization (IMO); the IMO states that it is essential to restrict the amount of carbon dioxide emissions and other greenhouse gases produced by a ship route [31]. Since air pollutants are amongst the most common forms of emissions from ship structures and there is a propensity for atmospheric levels of greenhouse gases to increase significantly in the next 20 years, the environmental consequences must be investigated for the ship mission decision making process. Within the proposed multi-attribute risk assessment of marine vessels, the repair loss, fatigue damage, total travel time, and CO_2 emissions are considered as consequences. Since there have been no significant research efforts regarding risk-based, multi-attribute shipping route decision making, it is necessary to develop sound approaches to effectively assess the risk associated with marine vessels.

The ship routing decision making procedure also greatly depends upon the risk attitude of the decision maker toward the consequences associated with structural performance. Utility theory is incorporated within the decision making framework to account for the attitudes of a decision maker. A utility function that measures the value of a particular alternative to the decision maker is established for each attribute. In order to account for various sets of units corresponding to each type of consequence, Multi-attribute Utility Theory (MAUT) is employed to convert each attribute (i.e., repair loss, fatigue damage, travel time, and carbon dioxide emissions) to a consistent unit. A balanced combination of various attributes can be determined by employing MAUT [33]. The goal of MAUT, within this context, is to transfer the criteria under investigation into one combined value; this multi-attribute performance metric is representative of ship performance during a particular mission. Risk assessment has not been widely incorporated within previous decision support systems, except for a few studies [6,7,10,43]. Additionally, to the best knowledge of the authors, MAUT has not been adopted in the ship routing decision making process. By employing utility theory, the decision maker's attitude can be incorporated into the decision making process. Furthermore, attributes with various units can be all converted into a singular utility value that is always bounded by 0 and 1.

Overall, the approach adopted within this paper focuses on the estimation of ship safety considering flexural and fatigue damage and provides a sound ship routing risk assessment procedure. Additionally, the generalized framework developed herein performs a variety of tasks, including, but not limited to quantifying the flexural and fatigue performance of a ship structure and employing MAUT to evaluate ship mission performance. A structural reliability approach is utilized to compute the probability of failure considering the uncertainties associated with structural capacity and load effects. The attitude of the decision maker is also considered herein using utility theory. The proposed multi-criteria based decision making management approach for ship structures has the ability to determine mission performance considering repair loss, fatigue damage, total travel time, and carbon dioxide emissions. Ultimately, the presented methodology can assist decision makers in making informed decisions concerning ship routing. The approach is applied to the Joint High-speed Sealift Ship (JHSS) [11] in order to illustrate the capabilities of the proposed methodology.

2. Framework for the multi-criteria decision making

The first step of the ship routing management procedure is to define the structural information and route alternatives corresponding to the ship under investigation. Next, the limit state and loading cases associated with ship structures should be determined. A flowchart outlining the proposed framework is shown in Fig. 1. The environmental conditions (e.g., sea states) must be identified in order to determine the loading scenarios. Each sea state is regarded as the general condition of the free surface on a large body of water and may be characterized by certain significant wave heights and frequencies of these waves. The limit state corresponding to flexural failure is incorporated within this approach. Additionally, the uncertainties involved with this limit state are considered within the risk assessment procedure. Risk is defined as the product of adverse consequences and probability of occurrence associated with a given limit state. In order to quantify the risk, the probability of failure associated with a given limit state should be determined first by using simulation and/or first/second order reliability analysis. Then, given the specific consequences of structural failure, the risk can be assessed accordingly. Finally, each decision should be made on basis of risk, which associates the probability of occurrence of specific event with the consequences. Spectral-based fatigue damage is also included as a performance criterion regarding ship routing decision making. The

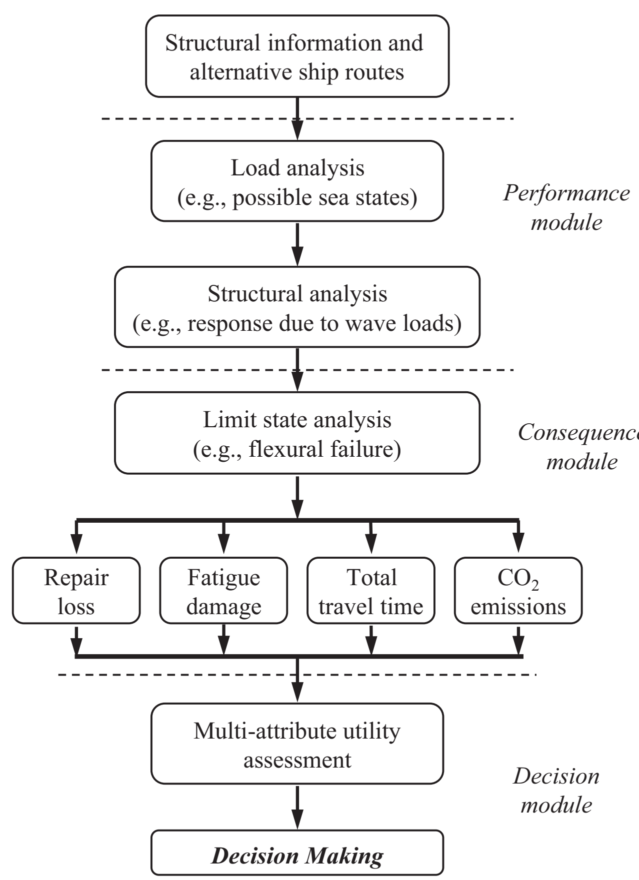

Fig. 1. Flowchart for the decision support system.