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A study on the performance of cascade hard sails and sail-equipped vessels

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ABSTRACT

This study proposes a type of hard sail and investigates its potential use on commercial vessels for utilizing wind energy. We focus on the performance of cascade sails and consider the aerodynamic interaction between the sails. To obtain the lift and drag coefficients of the sails, wind tunnel testing and a two-dimensional simulation code based on the boundary element method with vortices are used. According to the change in distance and attack angle of each sail in the cascade, the best setup parameter is investigated, and the aerodynamic interaction is analyzed. From the viewpoint of the sailing performance of the vessel, our results demonstrate that cascade hard sails can significantly reduce fuel costs for commercial vessels.

1. Introduction

Vessels are one of the most environmentally friendly forms of long-distance transportation. However, greenhouse gas production from these vessels increases each year with the growing global economy. IMO (2009) reported that the volume of goods transported by sea increases 3% each year and will reach 3.3 times the current volume in 40 years. It is almost impossible to use conventional vessels to cut total CO_2 emissions in half by 2050 to meet the Kyoto Protocol Target Achievement Plan. Therefore, green vessels that partially or entirely use clean energy such as solar and wind power are necessary. In this paper, the authors focus on the use of wind energy by sails for green vessels.

In order for these vessels to be efficient using wind energy, high-performance sails with a large wing area are necessary. A comparison of the maximum lift coefficients for various soft sails, hard sails and rotor sails based on wind tunnel tests was introduced by Bergeson and Greensward (1985). They circumstantiate that rotor sails usually have the highest lift coefficients, and hard sails have higher lift coefficients than soft sails. However, it is well known that it is somewhat difficult to upsize rotor sails because of their mechanical structure. Therefore, high performance, a large wind area, and simple mechanical structure are necessary when considering future wind-driven merchant vessels.

Since the oil crisis in the 1970s, hard sails have been proposed for and applied to some vessels, as shown in Fig. 1 (Fujiwara, 1980). These vessels with hard sails successfully reduced fuel consumption by 10% (e.g., Matsumoto et al., 1982). Recently, Ouchi et al. (2013) proposed a telescopic structure for hard sails and tried to utilize wind power by equipping multiple hard sails instead of using fuel oil for engines. They concluded that for a cape-size bulker with nine sails, the energy savings ratio at a speed of 14 knot is estimated to be more than 80% in the appropriate wind conditions. These studies, as examples, proved that using hard sails is a good way to help reduce the fuel consumption of vessels.

The aerodynamic characteristics of hard sails were investigated in many previous studies. A cascade hard sail bulker was studied using wind tunnel tests (Ingham and Terslov, 1985). Fujiwara et al. (2003) proposed a hybrid sail and evaluated its aerodynamic characteristics. They investigated the sail–sail and sail–hull interaction effects of a hybrid sail in a wind tunnel experiment (Fujiwara et al., 2005). Recently, Nakashima et al. (2010, 2011) and Yamashita et al. (2011) investigated the aerodynamic interaction phenomena between each hard sail in the cascade by wind tunnel measurements and numerical simulations and they corroborated that the sails in the cascade were set independently and can provide higher aerodynamic performance than that in a parallel arrangement. There are several problems with the hard sails in these previous studies. For example, when the vessel is tacking, all of the sails have to turn to large angles; the hybrid sail needs mechanical improvement for easy steerage. Moreover, the distance between sails was only decided by the structure of the vessel, such as the length of the hatch covers, and did not consider the performance of the cascade sails.

In this study, hard sails made of advanced lightweight materials such as CFRP (carbon fiber reinforced plastic) or GFRP (glass fiber reinforced plastics) may lead to an automatic mechanism for reefs

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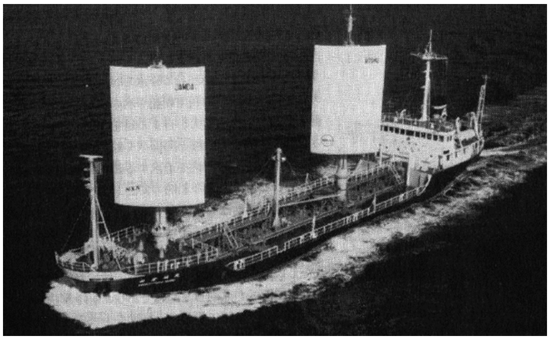

Fig. 1. Photo of hard sails equipped on a vessel in the 1980s (Fujiwara).

and for high performance. To achieve future green vessels with hard sails, it is necessary to consider such aspects as reef mechanisms, structural evaluation, and performance.

In this paper, the authors mainly focus on the aerodynamic effect of the hard sails that one of the authors developed. First, a feasibility study on a new wing sail is discussed. We had to consider the performance of a single-sail design to set a baseline for a multi-sail concept. The lift force and the drag force of the single sail are measured at different cambers and attack angles using a wind generator.

Hard sails are necessary for sail-equipped vessels to produce enough thrust. Therefore, the aerodynamic interaction between sails must be considered. A cascade of the three wing sails was set up under specific parameters in the experiment, including different attack angles and different distances between sails. The authors also developed a two-dimensional simulation code based on the boundary element method with vortices as its source. Using this code, the best setup parameters are investigated, and the aerodynamic interactions are analyzed. Also, from the viewpoint of the sailing performance of the vessel under wind, the ship speed, the drift angle, and the rudder angle are discussed in this paper.

2. Concept of rig design

2.1. High-performance wing sail

In the design of hard sails, in order to achieve high performance, an airfoil shape is commonly used. The airfoil shape can be classified into two basic types: a symmetrical wing and an asymmetrical wing. Symmetrical wings can adjust to different wind directions by controlling the mast accordingly. However, the lift force of symmetrical wings is less than that of asymmetrical wings. In this study, asymmetrical wings are used in the design of the high-performance wing sails. The Airfoil Investigation Database was referred to when determining the sail shape. When choosing the sail shape, high maximum lift coefficients, a high lift drag ratio, and a large thickness (for sufficient structural strength) were considered. Eventually, EPPLER420 was chosen as the new sail.

2.2. New mast design

Ouchi and Uzawa proposed a telescopic structure with a single mast for the symmetrical sail, as shown in Fig. 2. As mentioned above, to achieve high performance, the best design is an asymmetrical sail. Therefore, a new rig design is proposed in this paper; it is called a double slewing mast and includes a main mast and a sub-mast, as shown in Fig. 3. The sub-mast is in the tail of the airfoil part, and it can rotate the plate part. For different wind directions, the camber of the sail can be controlled appropriately by adopting a double slewing mast system.

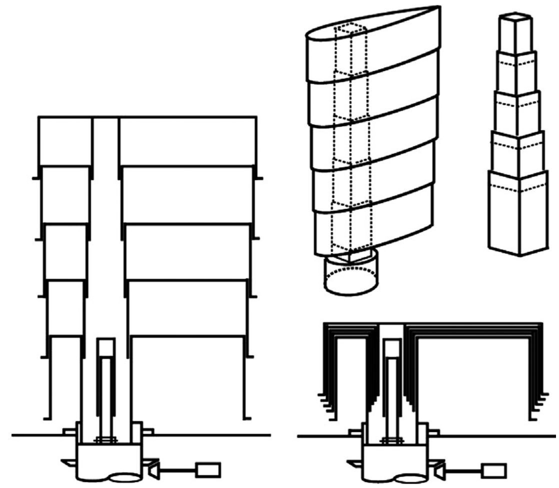

Fig. 2. Telescopic structure (proposed by Ouchi, 2009).

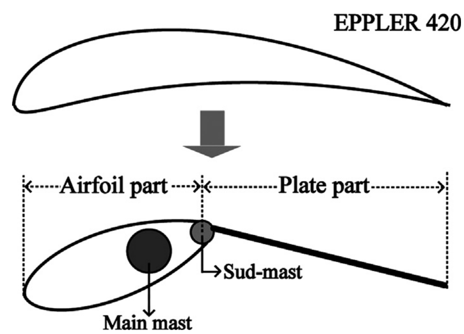

Fig. 3. Sectional form of sail.

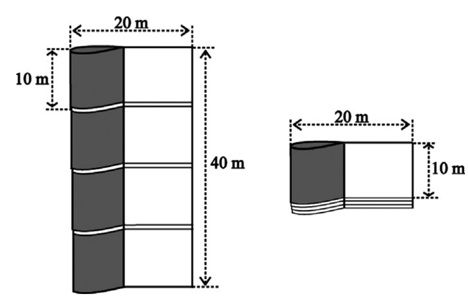

Fig. 4. Side view of sail.

2.3. New sail type

Based on these concepts, a new type of sail was developed. Fig. 3 shows the sectional shape of the sail. The sail is divided into an airfoil part and a plate part. The airfoil part has a symmetrical shape to accommodate all wind directions without a slat. The plate part is a plate, which can reduce the weight of the sail, and it is the simplest shape that keeps the entire sail an asymmetrical wing. The sub-mast is in the tail of the airfoil part, and it can rotate the plate-part. The camber of the sail can be adjusted for the specific wind direction. This new type of sail was named a variable-camber sail (VCS). Fig. 4 shows the side view in the unfurled state and reefed state. In this study, to better understand the fundamental performance of the VCS, end plates and current plates were not used.