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Contributions to EEOI and EEDI by Wind Challenger Ships

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Abstract

To establish a low carbon society, reduction of CO_2 emission from fossil fuels is vital. Therefore, developments of technologies for this purpose have become an important global issue. To fulfil the requirement in marine transportation, international protocols EEOI (Energy Efficiency Operational Indicator) and EEDI (Energy Efficiency Design Index) were instituted by the IMO (International Maritime Organization). However, compliances to these protocols are strenuous and at this moment reduction of ship speed seems to be the only solution, which may stall the growth of the global economy. The WCP (Wind Challenger Project) was initiated at the University of Tokyo in Oct. 2009 as a joint industry project. The WCP has been developing a huge rigid sail system that can profitably utilize the marine wind energy. The first WCP ship was designed for an 180,000 DWT cape size bulk carrier. The ship-plan and its design concept were presented at the 5th PAAMES and AMEC2012. As a second step, a case study on an 84,000 DWT post Pana-max bulk carrier has been conducted for fixed shipper and a service route. A large power gain by the rigid sail system is expected. In this paper, the detail plan and propulsive performance of the aforementioned ship are presented. In order to effectively exploit wind power, an optimum ship routing method has been developed based on the recent numerical weather prediction. From this research, it is found that the new weather routing technique as well as the sail system assures smaller values of EEOI and EEDI without a reduction of ship speed.

Keywords: Sail assisted ship, Wind power, Weather routing, EEDI, EEOI

1 Introduction

The Wind Challenger Project was initiated in 2009 at the University of Tokyo jointly with the Japanese major shipping companies, ship builder and marine equipment companies. The main target is the development and design of new ships that extracts ocean wind power to propel the ship and reduce the CO_2 emission. The ship is equipped with extraordinarily large rigid sails on board. The sail has a crescent wing section and is made of advanced light materials such as CFRP or GFRP composites. Each sail can be telescopically extended or reefed, and its sail angle is automatically controlled against the wind direction.

The first Wind Challenger Ship was a Cape size bulk carrier equipped with 9 rigid sails (total sail area 9,000 m^2). A case study on fuel saving in realistic sea conditions of the Yokohama and Seattle route revealed that the WCP sail system reduces the propulsion energy by about 30% on average. **(Ouchi 2012)**.

In this paper, the detail plan and propulsive performance of the second Wind Challenger ship, the post Pana-max bulk carrier, are introduced (section 2). The power gain and the contribution to EEOI (Energy Efficiency Operational Indicator) are evaluated in section 3. The contribution to EEDI (Energy Efficiency Design Index) is investigated as well. The optimum ship routing method making use of the numerical prediction will be described in section 4. Conclusions follow.

2 Development and design of post Pana-max bulk carrier

The principal particulars of the second Wind Challenger ship, the post Pana-max bulk carrier which has 4 rigid sails, are provided in Table 1. Each sail (50m height, 20m width, 4m thick) is arranged on the centre line between the hatches. The wheel house is arranged on the forecastle deck to secure the front view. The artistic illustration of the ship navigating in the ocean is shown in Fig.1. At the harbor and under extremely strong weather conditions, the sails can be reefed as shown in Fig.2. Reefed sails are stowed on the hatch-end spaces and the heights of sails shrink to a level almost the same as the accommodation house.

Table 1 Principal particulars of the post Pana-max bulk carrier

Length (OA)	about 228.50 m
Breadth	36.50 m
Depth	19.89 m
Draft (design)	12.15 m
(scantling)	13.90 m
DWT (design)	70,300 ton
(scantling)	83,600 ton
Cargo Capacity	102,600 m^3
Cargo Space	5 Holds, 5 Hatches
Sail Area	4,000 m^2
Main Engine	9,965 kW×94.0 rpm
Service Speed (design)	14.3 kt
Complement	25 persons

Fig. 1 Image of the post Pana-max bulk carrier.

Fig. 2 Image of Sail at the reef mode.

In order to evaluate the thrust of the wing sail system, CFD analyses as well as wind tunnel tests were performed. The definitions of the thrust force and related parameters are illustrated in Fig.3. The optimum *Cx* values of total four sail system for each apparent wind directions (AWA) were investigated (Fig.4). The maximum *Cx* value is from beam to quarter lee directions.

Using those *Cx* values, the power gain from wind is calculated for various true wind angles and wind speeds at ship speed 14.3 knot (Fig.5). The discontinuities of the curve is associated with the reefing of the sail when the wind speed exceeds the threshold value.

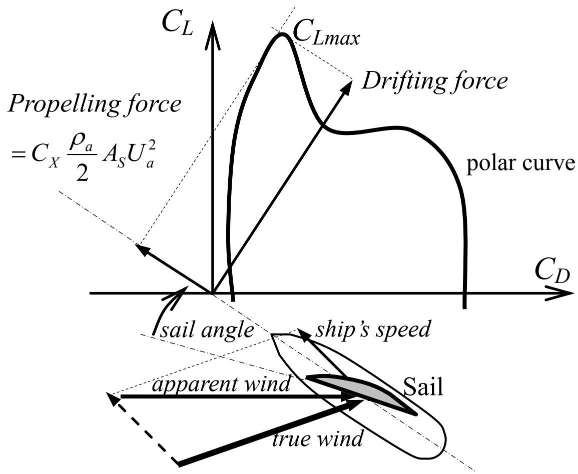


Fig. 3 Definitions of sail thrust and coordinate.

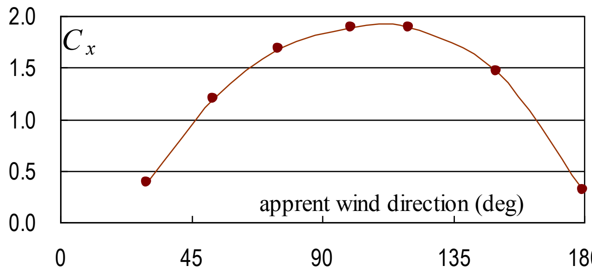


Fig. 4 Maximum *Cx* value of sails

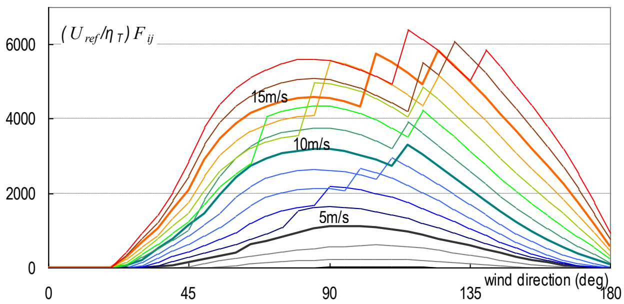


Fig. 5 Power matrix of the Wind Challenger post Pana-max bulk carrier (U_{ref}=14.3kt)

3 Contributions to IMO EEDI

3.1 Provisional calculation method for wind ships in IMO EEDI

IMO established an international regulation to reduce CO_2 emission from marine transportation. For newly constructed ships, the Energy Efficiency Design Index (EEDI), defined as the CO_2 emission (g) per ton mile, is required to be reduced by 30% of the present level at the final stage of Phase-3. However, since the propulsive efficiency of merchant vessels seems to have reached its limit, it may be difficult to comply with EEDI by just extending existing technologies. Particularly for low-speed merchant ships such as tanker and bulk carrier, there is little room for improvement of the hull efficiency because the hull resistance consists mostly of frictional resistance proportional to the hull area. Therefore, the regulation also permits the use of innovative energy efficient technologies such as air lubrication and wind propulsion in the calculation and verification of the EEDI.

EEDI Calculation Guidelines **(IMO MEPC. 1/Circ.815 2013)** provides methodologies of calculation, survey and certification of innovative energy efficiency technologies. According to the guideline, the available effective power (AEP [kw]) can be calculated by the following formula when wind propulsion systems is used.

$$\mathrm{AEP} = \frac{U_{ref}}{\eta_T} \sum_{i=1}^{m} \sum_{j=1}^{n} F(U_{ref})_{i,j} \cdot W_{i,j} - \sum_{i=1}^{m} \sum_{j=1}^{n} P(U_{ref})_{i,j} \cdot W_{i,j} \quad \textbf{(1)}$$

where, U_{ref}: ship reference speed in m/s, as defined in the EEDI calculation guidelines

$F(U_{ref})_{i,j}$: force matrix of the respective wind propulsion system for a given ship speed U_{ref}

$W_{i,j}$: global wind probability matrix

$P(U_{ref})_{i,j}$: matrix with the same dimensions as $F(U_{ref})_{i,j}$ and $W_{i,j}$ and represents the power demand for the operation of the wind propulsion system

η_T : total efficiency of the main drive(s) at 75% of the rated

$W_{i,j}$ is the matrix of wind direction and wind speed, provisionally defined by IMO, and should be unexceptionally applied for every ship. The probability wind matrix was proposed by Germany **(IMO MEPC 62/INF.34 2011)** based on a large volume of observation data along main international routes shown in Fig.6.

The probability of the wind direction is shown in the upper figure of Fig.7. Apparently, the probabilities of wind directions from fore and aft side are higher than that of beam wind. This is not necessarily advantageous for the sail assisted ships because the sailing efficiencies are lower in those wind directions.

The probability of true wind speed is shown in the lower figure of Fig.7. The maximum probability occurs at around 7.5 m/s that is almost the same as the conventional ship's cruising speed.

Although the IMO's probability wind matrix is not advantageous for sail assisted ships, this matrix will be used for the AEP calculation.

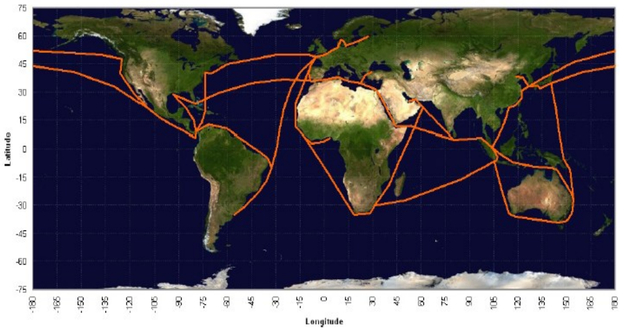


Fig. 6 Global route **(IMO MEPC 62/INF.34 2011)**

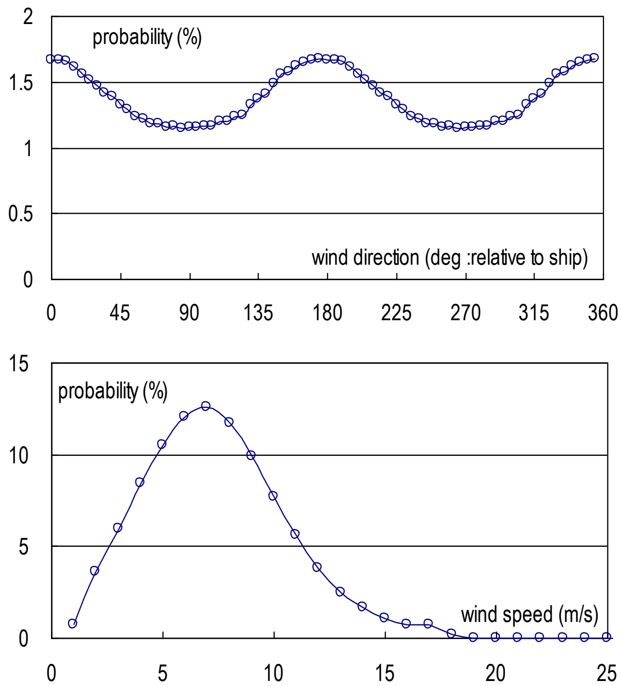


Fig. 7 Global wind provability matrix for EEDI

3.2 AEP calculation and the contribution to EEDI of Wind Challenger 84,000DWT bulk carrier

AEP calculation is applied to the newly designed Wind Challenger post Pana-max bulk carrier in full load condition. In case of no-sail, the output of the prime mover becomes 7,474 kW BHP at the cruising speed of 14.3kt. The force matrix F_{ij} produced by the sails are calculated for various wind speeds and wind directions. The driving power matrix P_{ij} is estimated to be 10 kW for each sail, since the sail angle is not frequently changed.

Making use of these data for the WC, AEP was estimated to be 895.2kw, which corresponds to 12.0% of the above BHP at this speed.

Although the calculated AEP by the IMO standard procedure is smaller than those from the previous weather routing techniques, it must be very useful for the reduction of EEDI since the reduction of hull resistance for low-speed ships is very difficult to realize. Sail assisted ships are expected to be an important tool to accomplish the EEDI reduction.

4 Optimal routing and contributions to IMO EEOI

The Wind Challenger exploits the state-of-the-art wind prediction and optimum ship routing technologies. Considerable reduction of energy consumption and emission is expected, which might change the global maritime logistics.

The ship routes of the Wind Challenger, inevitably deviates from the great circle. Therefore, to capture the winds most efficiently during the voyage, a completely different route, course or direction should be chosen when departing from a port. We first introduce the Wind Challenger Sailing Simulation (WCSS, Katori et al. 2012) developed to estimate the energy savings of the sail assisted ships. Next, the capacity of the WC ship is demonstrated by a test without engine support, resulting in a large detour from the great circle. A typical voyage across the Pacific takes about two weeks. The operation of the WC requires prior estimate of the wind condition, and therefore, uncertainty of the wind prediction affects the reliability of the estimated ship routes. Therefore, the dependence of the selected routes on the wind prediction is studied using ensemble members of the numerical weather prediction (NWP). Finally, to overcome the inevitable uncertainty of the NWP, a test was conducted updating the wind forecasts along the voyage.

4.1 Wind Challenger Sailing Simulation

Weather routing is a method used to minimize the voyage time or the energy consumption of a ship by selecting an optimized route (Weather Routing Research Group 1992). In Wind Challenger Sailing Simulation (WCSS), the energy consumption is minimized:

$$J \equiv \int_{t_0}^{t_f} EPP\left(\vec{U}\left(\vec{X},t\right),\Theta,\vec{\mathrm{V}}\right)dt \qquad \textbf{(2)}$$

where J is the cost function. The energy consumption EPP is determined by absolute wind velocity $\vec{U}$, the ship orientation Θ, and the ship velocity $\vec{\mathrm{V}}$. Punctuality is the constraint so that the voyage time $t_d = t_f - t_0$ is fixed while the ship trajectory $\vec{X}$ is determined by the optimization. WCSS searches for the optimized route in two steps. First, for a given engine power BWP, duration of the voyage along a great circle is determined t_G. Next, an optimized route with sail assistance at full engine power BHP is found by isochrone method. Inevitably, the duration $t_d < t_G$ as a result of wind thrust. Then, an optimized route for a reduced engine power $\alpha \times BWP$ is searched. This procedure is repeated until $t_d \cong t_G$. The final reduced energy consumption $\left(1-\alpha_{final}\right)$ is called the Saved Energy Ratio (SER).

Unlike Dykstra method which directly solves the minimization problem of (1), isochrone method conducts a piece-wise optimization. For each interval, say 6 hours, the furthest reachable points are computed. Those points will construct an envelope of the polar curves originating from the furthest reachable points in the previous time step. This piece-wise optimization is repeated until the ship reaches the final destination. The optimum route is then determined tracing back the routes in time. The isochrone method makes it easy to incorporate local wind conditions dependent on space and time, unlike Dykstra method which requires prior knowledge of the future wind conditions at all the points in space and time. The shortage is to miss a possible choice of a slow navigation at some point to gain largely the energy consumption in the future. For example, delaying a departure time from a port might result in successful capture of strong wind in the future and thus a large reduction in energy consumption.

4.2 Sailing without engine

To demonstrate the capacity of the WC ships, a routing simulation between Yokohama and Seattle was conducted without engine for the 180,000 ton Cape Size Bulk carrier equipped with nine rigid sails. In this case, the goal is to find the fastest route and thereby the $t_d \cong t_G$ constraint is removed. The duration was about 18 days, and the selected route largely deviates to the south from the great circle taking advantage of the local wind. Note that in this simulation, reefing was not considered but routes that the ship speeds exceed 15 kts were circumvented.

4.3 WCSS ensemble run

Prior study on the uncertainty of wind forecast revealed that the prediction skill rapidly degrades in the first 3 days or so (Nishida & Waseda 2012). This implies that the initial estimate of the route based on forecast wind can deviate largely from the optimum route utilizing the actual wind field. Twenty one datasets of the NCEP Global Ensemble (GENS) wind data was used for the simulation. For a great circle route, the mean SER was 31 % while the maximum and minimum SER from the 21 ensembles were 41 % and 25 % respectively. On the other hand, SER of the optimum route simulations varied largely between 92 % and 32 % whose mean was 49 %. The spread of the routes and the SER were surprisingly large, particularly for the optimum route simulations. To reduce the uncertainty of the estimate, we therefore conducted a simulation updating the wind field with the latest forecast.

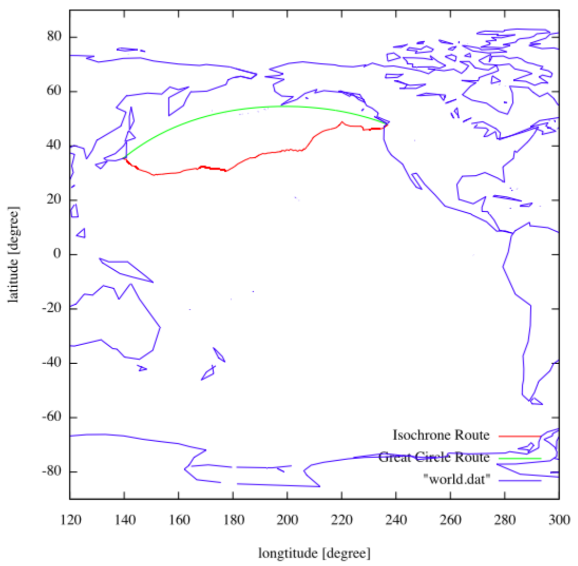
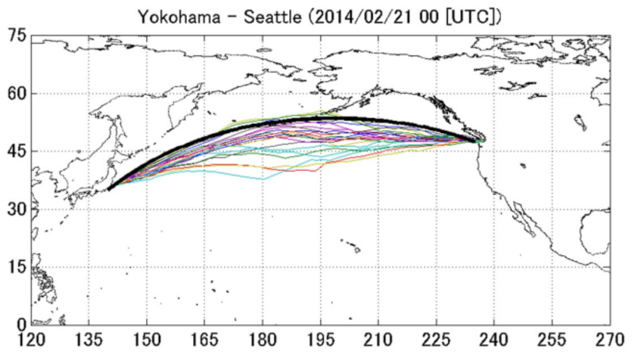


Fig.8 Optimum route without use of engine



Ensemble Member	1	2	3	4	5	6	7	8	9	10	11
GC	39.8	25.1	36.6	33.9	31.3	29.8	26.6	40.6	36.3	29.8	30.2
Opt	60.3	40.5	54.7	91.5	41.4	39.9	46.6	53.6	44.9	51.6	66.9
Ensemble Member	12	13	14	15	16	17	18	19	20	21	aver ge
GC	25.8	31.1	31.3	31.6	24.5	31.7	37.4	26.5	25.1	29.7	31.2
Opt	41.9	40.0	34.2	48.6	31.6	47.4	73.7	40.5	36.5	36.3	46.7

Fig.9 The optimum routes for the ensemble simulation using NCEP/GENS wind (top) and the resulting SER (bottom table). The black curve is the great circle.

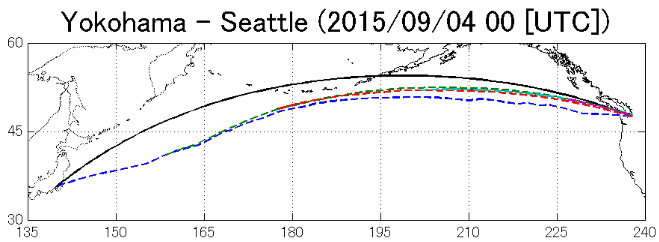


Fig.10 Initial optimum route (blue) and the updated routes at 3 day interval (green, red, and magenta).

4.4 Forecast simulation with NWP

For operational use of the WCSS, the NWP products will be utilized. An NWP data contains about two weeks of data and is updated every 6 hours. The initial record of each dataset is called the analysis and the rest the forecast. JMA GPV (GSM, MSM, LFM), NCEP-GFS, and ECMWF-NWP are the representative products available for use. The quality of these products were validated with in-situ wind measurements from buoy records, and assured that the correlation is high (between 0.85 and 0.95), with a relatively small bias dependent on the location (Waseda et al. 2014). In this study, NCEP GFS winds were used. The forecast error was estimated to reach about 30 % in three to five days, which is consistent with the JMA GENS analysis. We therefore, updated the wind data every 3 days. The simulation was conducted for a 84,000 ton BC with one telescopic solid wing sail (60 m height, 15 m width, 4 m thick).

The procedure is the following: first, the 384 hours forecast will be used to estimate the optimum route with WCSS (blue line of Fig. 10). At day 3, the WCSS run is repeated with the latest forecast wind, starting from the ship location at day 3 (green line of Fig. 10). This procedure is repeated every 3 days. In this simulation, the ship track largely deviated from the great circle in the first three days, while the effect of updating the wind forecast was not as large after the 6th day. This is because there was a typhoon near Japan, and therefore, a large detour in the first 3 days was most effective. Indeed, the SER was 13 % for the overall voyage, 8 % after the third day, 3 % after the 6th day, and no saving after the 9th day. Certainly, when the wind speed is low, uncertainty due to wind is irrelevant. It is therefore conjectured that a more frequent update of the wind product is needed under strong wind condition.

5 Conclusions

In the present paper, an overview of the Wind Challenger Project, a Joint Industry Project led by the University of Tokyo, was given. Two types of ships were studied (180,000 ton Cape size BC and 84,000 BC) with variations of the number of solid wing sail (9, 4 and 1). The result of the CFD and model tests of the thrust coefficients of the wing systems and the power matrix considering the reef with the telescopic wing sail were introduced.

The EEDI calculation has been tried to evaluate the performance of the Wind Challenger ship. Based on the wind probability matrix provided by the IMO-EEDI, the power reduction was only about 12 %.

By conducting a sailing simulation utilizing numerical weather prediction data, we have shown that the reduction of energy consumption on average is more than 30 %. The estimated energy saving is subject to uncertainty of the wind forecast, and therefore, sensitivity tests were conducted resulting in a large variability of the estimate ranging between 30 to 90 %. Upon operation, the wind data should be updated. A preliminary test updating the wind at 3 day interval was conducted. The result implied that more frequent update of the wind is favorable under strong wind condition when the maximum reduction of energy consumption is expected.

Overall, we are optimistic that the energy saving of the sail assisted ship is much larger than what can be inferred from the EEDI procedure. This may powerfully contribute to the EEOI of shipping company. More work is warranted to quantify this final point.

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