Route planning of a fishing vessel in coastal waters with fuel consumption restraint

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ABSTRACT: Multi-objective route optimization procedure is applied to a 29 m vessel during its transit from a port in Portugal origin to a zone in Norway. Seakeeping responses at sea are assessed according with the strip theory and direct pressure integration is adopted for the estimation of the added resistance. The performance and the exhaust emissions of two similar four-stroke marine turbocharged diesel engines are calculated for different speeds and loads using a developed code implemented in Matlab. The simulation results are validated using data from a real engine. Finally, the integration of an operative weather forecast system allows the identification of the set of most favourable routes among which the Shipmaster can select the preferred one according to his/her experience and supported by a flexible ranking method.

1 INTRODUCTION

Fishing vessels are particularly exposed to hazards caused by meteorological factors. Being the fleet composed by a significant number of small ships, the regulation has historically been less severe than the one for large merchant and passenger vessels. Moreover, economical reasons force the fishermen to operate even in unfavourable weathers. These factors led to a significant accident rate and the highest rate of vessel losses (EMSA, 2014). Seasickness, hazards and injuries including in some cases loss of lives has been reported (Antão et al., 2008).

Various statistical studies aimed at identifying the main causes of accidents have been conducted in the past. Wang et al. (2005) studied a worldwide dataset of fishing vessel accidents recorded during the 90’s, it has been shown machinery damage as the most probable occurrence followed by foundering, flooding and grounding with probabilities of 65.97%, 15.41%, and 8.38%, respectively. A more recent study on three Spanish fishing vessels accidents resulting in loss of lives and ships were presented by Perez-Rojas et al. (2006). Antão & Guedes Soares (2004) highlighted the need of improving the operations and safety of fishing vessels as the conclusion of the study of a sample of accidents in a period of over 20 years including nearly 40,000 claims resulting in more than 350 deaths.

While the issues related with machinery damages can be reduced with more attention on the mainenance of the engines, many progresses can be done from the seakeeping and operational point of view and with the adoption of a more advanced technology including improved computer mapping software, weather routing and e-navigation.

Although the literature on hydrodynamics of fishing vessels is limited as compared to other commercial ships, interesting studies on both numerical analysis and measurements can be found in Obreja et al. (2010), Datta et al. (2011) and Tello et al. (2011). The method here adopt the procedure suggested by Guedes Soares et al. (1995) to investigate the seakeeping performance of a group of fishing vessels operating in the Portuguese coast and followed by Fonseca & Guedes Soares (2002) to investigate the sensitivity of the expected ships availability to different seakeeping criteria.

Besides the problems related with safety and seakeeping performance, efforts in reducing the fuel oil consumption are needed, in fact the incidence of fuel on the overall operating cost is significant reaching rates 80% in a beam trawl fishery (OECD, 2010), and Eayrs et al. (2012) showed how the highly volatile prices of fuel may jeopardize the profitability of this activity. Moreover, the importance of energy efficiency and reduction of CO₂ and NOₓ emissions is increasing also in the maritime fishing industry as shown in Latorre (2001), and Hua & Wu (2011). The actual propulsive performance in any required operational condition is calculated through a numerical simulation model developed for the selected four-stroke marine diesel engine derived by an extension of the two-stroke engine model proposed in Tadros et al. (2015).

In this paper all these factors are considered in order to optimize the navigation from the harbour to the working area, identifying the most favourable path and speed through a multi-objective genetic algorithm aimed at reaching the destination in the required time, minimizing the fuel consumption and emissions, and
the risk. For small vessels operating in the vicinity of the coast the navigation may have a small contribution in terms of consumption, emission and risk comparatively to the trawler activity; nevertheless, open water fishing vessels may be required to cover long distances in harsh seas before reaching the fishing area. This is the case of the Portuguese fishing vessel considered in this paper, whose body plan is shown in figure 1, travelling up to the Norwegian Sea.

The rest of the paper is organized as follows: in section 2 the methods applied to model the ship in term of seakeeping responses and propulsion system performance are described; section 3 gives an overview on the wave forecast system used for the prediction of the weather scenario; section 4 outlines the main features of the optimization method; the simulation and results are presented in section 5, while conclusion and final remarks are discussed in section 6.

2 SHIP MODELLING

Ship performance in operation varies significantly from still water condition. Waves degrade the ability to carry out the mission since the ship experiences increased and dynamic loads, which typically cause an added resistance with a reduction of speed of advance, a decrease in the efficiency of the propulsion system and the oscillatory motion of the hull in the six degrees of freedom. The latter may also result in unsafe situations, imposing a change of course or a voluntary speed reduction. This is even more important for fishing vessels due to their high exposure to risk, where reducing the ship motions can facilitate the operations and reduce injuries and fatalities of fishermen.

Ship dynamics is determined by complex interrelation of loads whose combined effect is sometime hard to predict. Even the most experienced seaman can benefit from scientific methodologies and innovative tools to minimize the negative effects of the human factor, providing all the necessary information for a more information aware decision process. One of the main difficulties is due to the fact that ship performances must be assessed in the conditions the ship is asked to face, not only in the design condition. A complete model of ship dynamics and propulsion system is therefore required. The more precise the modelling, the more reliable the final results can be expected, always considering the uncertainty always embodied in weather prediction and the necessary trade off between reliability and computational effort.

2.1 Seakeeping responses

In the present approach the hydrodynamic calculations are carried out off-line with a computer code based on the strip theory (Salvesen et al., 1970), which provides the Response Amplitude Operators (RAOs) of the motions. The imposed linearity causes the results to be reliable only for small waves. This limitation however does not dramatically affect the results, in fact, even if the actual values can suffer some error, the qualitative comparison of different condition is still valid and the results at higher sea-states are mostly used as a threshold on the operable scenarios.

The RAOs express the ship dynamics in the frequency domain with respect to the exciting forces. Associating the RAOs with a given wave spectrum ($S_\zeta$) the ship response spectra ($S_R$) can be easily determined by (e.g. Guedes Soares 1990):

$$S_R(\omega, \theta) = RAO(\omega, \theta) \cdot S_\zeta(\omega, \theta)$$

Since the sea-state is modelled as a stationary, zero mean, Gaussian process and because the responses are linear, a Rayleigh distribution describes the amplitudes or the peaks of the processes, according to which the probability of exceeding the level $r$ is given by:

$$Q_\zeta(r) = \exp \left( - \frac{r^2}{2\sigma^2} \right)$$

where the variance of a record $\sigma^2$ is given by the zero order moment of the response spectrum as:

$$\sigma^2 = m_0 = \int_0^{2\pi} \int_0^{\infty} S_\zeta(\omega, \theta) d\omega d\theta$$

Seakeeping performance can be computed in various conditions and their relevance depends on the type of ship and the mission of the trip. For a fishing vessel important factors to determine the operability may be green water and lateral acceleration which may compromise the capability of working on the deck or cause injuries or falls. Use of the derived Motion Induced Interruptions index (Baitis et al., 1983) can be done to evaluate the possibility to work on the deck. Slaming and vertical acceleration are also worth to be considered due to their effect on hull structure and comfort on board.

For the green water effect, the freeboard exceedance is a necessary, but not sufficient condition. If the speed is not too low, in fact, most of the time the exceedance of the freeboard does not imply a green water event. Nevertheless for this study the probability of deck submergence is considered to be a good and conservative indication and it is computed by:

$$P_{Fe} = \exp \left( - \frac{F_e^2}{2C^2_\zeta} \right)$$
where $F_e$ is the effective freeboard and $C_S$ is a coefficient to include the swell-up effect, here neglected.

The criteria on the vertical and lateral acceleration, being varying quantities, are given on the root mean square (rms) of the variance of the acceleration spectrum as:

$$\text{Acc}_{\text{rms}} = \sqrt{D_r}$$  (5)

A slamming event occurs when the keel emerges from the water, meaning that the relative motion is greater than the draft, and, later on, impacts on it with a speed higher than the critical value calculated according to Ochi (1964):

$$V_{CR} = 0.093 \sqrt{gL}$$  (6)

Thus it implies the knowledge of the relative motions and velocity at the bow. The probability of keel emergence is:

$$P_{ke} = \exp \left( -\frac{D_{ke}^2}{2C_S^2 D_{rel}^2} \right)$$  (7)

where $D_{ke}$ is the actual keel draft, which should take into account the trim, the sinkage and the ship’s own wave. $D_{rel}$ is the variance of the relative motion on the bow.

The probability to impact with a speed higher than the critical value is:

$$P_{CR} = \exp \left( -\frac{V_{CR}^2}{2C_S^2 D_{rel}^2} \right)$$  (8)

where the variance of the relative velocity on the bow is used.

From the previous considerations and assuming in first approximation the relative motion and velocity to be independent yields:

$$P_{sl} = P_{ke} \cdot P_{CR} = \exp \left( -\frac{D_{ke}^2}{2C_S^2 D_{rel}^2} - \frac{V_{CR}^2}{2C_S^2 D_{rel}^2} \right)$$  (9)

The definition of the limits not to be exceeded for any of those seakeeping criteria are not univocally defined and off course the criteria and prescribed values are different according to the ship type and purpose. Several seakeeping criteria related with the absolute motions amplitudes and motions relative to sea, have been proposed and they have been obtained mostly from the experience onboard of ships. In the literature some important reference can be found in Aertssen & Sluis (1972), Nordforsk (1987) and Dubrovski (2000). Apparently there are no published criteria specific for fishing vessels, and for this reason the authors have used for illustrative purposes a set of criteria that in fact were adapted from other types of ships. These criteria are passed to the code by an input file that can be easily accessed and modified by the user if a different strategy is required. At this stage the limits are set as described in table 1.

Besides acting as constrains to ensure the safety limits not to be overstepped, safety can also be included in the objectives to minimize the risk and/or increase the comfort. In this case all responses must be reduced to a single factor, a risk coefficient

$$RISK_{coef} = \frac{\max (C_{i_{\text{max}}}) + \max (C_{i_{\text{mean}}})}{2}$$  (10)

where $C_{i_{\text{max}}}$ and $C_{i_{\text{mean}}}$ are coefficients related to the ratio between the maximum/mean responses and their limits and $C_i$. The risk is thus evaluated in similarity to the concept adopted to define the seakeeping operability limit (see Nordforsk, 1987, fig. 3.3). The ratio aims to normalize all the seakeeping effects in a value in the range $[0,1]$ depending on the distance from the respective limit, such as 1 corresponds to the most extreme conditions that the ship can stand. All the effects are however stored and are available to the user in the setting of the optimal routes.

### 2.2 Ship resistance

The still water resistance is calculated according to the method of Holtrop & Mennen (1982) which is an approximate procedure widely used at the initial design stage of a ship. The method is based on regression analysis of random model experiments and full-scale data.

The calculation of the added resistance under the effect of irregular sea-states is assessed by the direct pressure integration procedure developed by Faltinsen et al. (1980), which provides relation between the added resistance ($R_{AW}$) and the wave amplitude ($a$) in terms of:

$$\Phi_{AW}(\omega, \theta) = \frac{R_{AW}(\omega, \theta)}{a(\omega, \theta)^2} \cdot \frac{\sigma_{AW}(\omega, \theta) \rho B^2 L^{-1}}{\sigma(\omega, \theta)^2}$$  (11)

where $\sigma_{AW}(\omega, \theta)$ is the added resistance coefficient as suggested by many model test (Gerritsma et al., 1961). For a pre-defined wave spectrum $S_\zeta(\omega, \theta)$ describing the sea-state $H_\zeta, T_\zeta$ the mean added resistance can be thus assessed by the equation:

$$\overline{R}_{AW} = 2 \int_0^{2\pi} \int_0^\infty \Phi_{AW}(\omega, \theta) S_\zeta(\omega, \theta) d\omega d\theta$$  (12)

At this stage the system only allows to consider the effect of waves, however wind and ocean surface currents may also have a not negligible impact and will be included in future implementations.
Table 2. Technical data of MAN V8-1000.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore (mm)</td>
<td>128</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>157</td>
</tr>
<tr>
<td>No. of cylinders</td>
<td>8</td>
</tr>
<tr>
<td>Displacement (liter)</td>
<td>16.16</td>
</tr>
<tr>
<td>Number of valves per cylinder</td>
<td>4</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17</td>
</tr>
<tr>
<td>BMEP (bar)</td>
<td>23.73</td>
</tr>
<tr>
<td>Piston speed (m/s)</td>
<td>12.04</td>
</tr>
<tr>
<td>Engine speed range (RPM)</td>
<td>1200–2100</td>
</tr>
<tr>
<td>Gear reduction ratio</td>
<td>7.5</td>
</tr>
<tr>
<td>Specific fuel consumption (g/kW·h)</td>
<td>223</td>
</tr>
</tbody>
</table>

The total resistance in any sea-state can be then easily computed in order to identify the propeller working point and the power and speed (number of revolution per minute RPM) required from the main engine.

2.3 Prime movers

2.3.1 Engine specifications

The two main engines installed are selected from MAN (http://www.engines.man.eu/) marine engine V8-1000, each one of them is a 4-stroke direct injection 8 cylinder in 90°V design with a speed range of 1200–2100 RPM. The intake pressure and temperature are set at atmospheric conditions, i.e. 100 kPa and 298°K, respectively. The maximum power of each engine is 735 kW at 2300 RPM and the main information of the engine are summarized in table 2.

2.3.2 Engine model

The performance of the simulated engines and the attached turbochargers are calculated for different engine speeds and loads. The engine specifications, fuel injector, fuel characteristics and atmospheric initial conditions are the main input data for the numerical model. The turbocharger, intercooler, engine processes, heat release rate (HRR) and heat transfer are the different modules considered during the simulation.

The engine processes are calculated as function of the crank angle according to the first law of thermodynamics (Heywood, 1988) taking into considerations the heat transfer suggested by Woschni (1967). The Wiebe function expressed in (Watson et al., 1980) is used to calculate the fraction mass of the fuel burned during the combustion process. The cylinder pressure \( P \) and the corresponding cylinder volume \( V \) are used to calculate the indicated work per cycle by integrating the area enclosed on the P-V diagram. The exhaust emissions are calculated using the chemical equilibrium of the combustion equation using the element potential method (Smith & Missen, 1982). The CO\(_2\) emissions depend on the type and the amount of fuel used. However, the NO\(_x\) emissions are calculated using the integration over all elements that give the final average of NO\(_x\) concentration in the cylinder.

Figure 2 represents the operative conditions of the engine in terms of power rate vs speed rate with the contours of the specific fuel oil consumption (SFOC) and the \( \text{CO}_2 \) and NO\(_x\) emissions. The propeller curve for still water condition is also superposed and the red star indicates the required RPM and power absorbed by the propeller at the speed of 11.5 knots, which is the maximum speed in regular continuous operation.

The simulation results of the exhaust emissions classified the engines under tier 2 with NO\(_x\) emissions less than 7.7 g/kW·h at the rated speed according to the NO\(_x\) technical code (MEPC, 2008). The simulation results are validated using a real data of four-stroke marine turbocharged diesel engine provided by the manufacturer as mentioned above.

3 OPERATIONAL WAVE FORECASTING SYSTEM

The availability of reliable daily operational weather forecast is essential to assess the scenario in which the ship will operate in the imminent mission and is
a required input for the weather routing code. Modern phase averaging third generation wave models (Komen et al. 1994) predict the spatial and temporal evolution of the directional spectrum solving the spectral energy equation. Those methods are recognized for their accuracy, but uncertainties introduced in the initial conditions may propagate deteriorating the results especially for medium and long-term forecasts. Moreover, although these models can now be considered well established, a wide number of products are available with different resolutions, domains (from regional to global) and quality. A review of the main available products can be found in Bidlot et al. (2002). Often shipping companies already have some agreement with a meteorological institute to be supplied with updated weather forecast, thus the software should be able to digest different inputs.

An operational wave forecasting system for the North Atlantic is now available as the evolution of the one presented in Guedes Soares et al. (2011). It includes the Fifth-Generation NCAR/Penn State Mesoscale atmospheric Model MM5 (Dudhia et al., 2000) and the wave models WAM for the ocean area and SWAN for the coastal areas and port approaches (Rusu & Guedes Soares 2013). The system has been validated by performing comparisons with both wind and wave measurements. Results are provided in a grid covering the whole north Atlantic sub-basin in the range of $[2^\circ, 80^\circ]$ of latitude and $[-90^\circ, 33^\circ]$ of longitude with spatial resolution of 0.5° and 6 hours time resolution. Intermediate conditions are assessed by linear interpolation in both space and time.

4 OPTIMISATION ALGORITHM

The basis of optimisation method adopted has been described in Vettor & Guedes Soares (2015). It is based on a flexible C++ code that integrates the upgraded Strength Pareto Evolutionary Algorithm SPEA2 (Zitzler et al. 2002) which demonstrated good performances in comparison to similar techniques. Three genetic operators are used, namely crossover, mutation and migration, allowing the initial generation to improve in the evolution up to identifying after a proper number of generation the set of the most favourable routes describing the Pareto frontier.

In this work the code has been improved by including an a priori single objective optimisation using a modified version of the Dijkstra's algorithm (Dijkstra, 1959) to take into account the dynamics of constrains and objectives. Through this a priori optimisation a number of individuals with optimal performances on respect with different objectives are inserted in the first generation. This scheme allows to reach the Pareto frontier in a much lower number of generations, reducing significantly the computational effort and time.

Moreover, a ranking method has been developed aimed at selecting the preferred routes among the most favourable set according to the importance given by the Shipmaster to the different objectives. The method takes into consideration the relative weights and allows for excluding routes whose performance are not considered sufficient or with a not relished path and for checking different options before the final selection. This contributes to give more choices and flexibility to the user.

As it is usually required in the route selection, the objectives to be optimised are the total fuel consumption, the duration of the navigation and the risk. The latter is estimated by means of a coefficient combining the maximum and average seakeeping responses on respect to their limits as indicated in table 1.

5 SIMULATION AND RESULTS

The developed weather routing code and engine model have been used together to optimize the route of a 29 m trawler vessel departing from the port of Figueira da Foz in Portugal on June 21st 2015 at midnight to reach the fishing area in the Norwegian Sea offshore the city of Bergen at a great-circle distance of 1273 nmi, thought, due to the British Isle, the shortest path is of about 1405 nmi.

On June 25th, 4 days after the departure, a storm is expected to reach the western Irish coast with SWH higher than 3 m. Thus, even though the possibility of circumnavigating the British Isles has been tested by the code, all the final routes pass through The Channel. As can be noticed in figure 3, due to the land border constrain, the path of the route may only experience minimal variation. Nevertheless, the optimization can still drastically influence the resulting route by modulating the speed in order to overcome a perturbation or let it pass, so as to make the trip more efficient.

In table 3 the main characteristics of the routes resulting from five different strategies are summarized. The first three cases correspond to a
Table 3. Characteristic of the route resulting from different selection criteria.

<table>
<thead>
<tr>
<th>Route</th>
<th>Faster</th>
<th>Cheapest</th>
<th>Safest</th>
<th>1st selection</th>
<th>2nd selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETA</td>
<td>June 26th, 07:59</td>
<td>June 30th, 08:47</td>
<td>June 30th, 18:53</td>
<td>June 28th, 05:44</td>
<td>June 26th, 21:55</td>
</tr>
<tr>
<td>Duration [hours]</td>
<td>128</td>
<td>225</td>
<td>235</td>
<td>174</td>
<td>142</td>
</tr>
<tr>
<td>Average speed [knots]</td>
<td>11.0</td>
<td>6.2</td>
<td>7.9</td>
<td>8.1</td>
<td>10.0</td>
</tr>
<tr>
<td>FOC [tonnes]</td>
<td>53.6</td>
<td>7.0</td>
<td>26.0</td>
<td>17.6</td>
<td>45.2</td>
</tr>
<tr>
<td>CO₂ emissions [tonnes]</td>
<td>172.9</td>
<td>22.7</td>
<td>83.9</td>
<td>56.9</td>
<td>145.7</td>
</tr>
<tr>
<td>NOₓ emissions [tonnes]</td>
<td>1.59</td>
<td>0.04</td>
<td>0.39</td>
<td>0.07</td>
<td>1.25</td>
</tr>
<tr>
<td>Risk coefficient [-]</td>
<td>0.32</td>
<td>0.09</td>
<td>0.07</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

single-objective optimization respectively on regards of duration of the trip, fuel oil consumption and safety.

As expected the first maintains the ship speed at the maximum allowed for most of the trip requiring slightly more than 5 days, consuming more than 50 tonnes of fuel. This is not the case of the second strategy that reduces the speed in order to make the engine operate in a range of lower specific fuel oil consumptions as suggested by the engine model (see figure 2.a.), but requiring more than 9 days to reach the destination. Finally, the safer strategy mostly tries to keep the path in calmer waters, but sometime forcing undesired paths.

Probably none of those options suits the mission requirements, a compromise must be found instead. The developed ranking method allows the Shipmaster to define the relative importance for each of the three objectives in order to select a more preferable route. In the example the same weight has been assigned resulting in the route described in the fourth column of table 3. Indeed, the so selected route is 51 hours shorter than the cheapest one, consuming about one third of the fastest and still maintaining a grade of risk similar to the safest route.

Even so, the Shipmaster may for instance realize that the navigation takes too long, while he wants to reach the fishing area within 6 days from the departure. The solution comes simply performing a constrained selection allowed by the ranging method, imposing to the duration of the journey not to exceed 144 hours and optimizing the other two objectives. As shown in the last column of table 1, this decision obviously results in more expensive, but the compromise will be acceptable and still allow saving about 16% fuel compared to the fastest choice.

The simulation showed some that some criticality on long-shore transits, which may increase if the passage through a channel is required; thus in the future more attention will be given to the domain modelling with a more refined grid in correspondence of critical locations and a dedicated algorithm to handle canal passages.

6 CONCLUSIONS

A complete ship weather routing system has been applied to optimisation of the navigation of a fishing vessel from the Port of Figueira da Foz in Portugal to the Norwegian waters. The factors influencing the route selection and the main objectives, namely the duration of the trip, the fuel consumption and the safety of the vessel and the crew have properly been assessed and the data used as an input for the code. The performance of the prime movers selected is simulated for different speeds and loads taking into considerations the variation of the air-fuel ratio for each case. The output results are calculated according to the main inputs presented above.

One of the most significant achievements of the method is the flexibility on the final selection of the most favourable path. In fact the genetic algorithm involved in the optimisation provides the best set of feasible routes in the Pareto meaning. Once the code has run all the routes are available for the final selection done by the Shipmaster through a simple ranking method that allows for weighting the objectives according with his preferences, but also rapidly changing the choice if not suitable for the mission, possibly applying a constrained selection.

The final solution, within the assumptions of the simulation, highlights the ability of the system to find the most favourable route satisfying the requirements of any different mission, both identifying the best path and modulating the speed in order to make the engine operate in an efficient range of power.

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