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# VESSEL PERFORMANCE ANALYSIS AND FUEL MANAGEMENT

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## ABSTRACT

A prototype Vessel Performance Monitoring and Analysis System (VPMAS) was deployed on a ferry to acquire need performance data, to help improve vessel performance and reduce fuel consumption. A paper published in 2014 described preliminary data trends observed, key performance indicators computed, data products explored and exploratory tools developed for crews to gain insight into their vessel operation. The current paper describes further analysis of the operational data for speed optimization in calm sea states and the preliminary development of trim optimization software.

It was found that trip durations around 7 hours (13.3 knots) use the least amount of fuel. The least amount of fuel is used when the excess distance travelled is minimized and the voyage time is optimized. There is a lot of leeway in terms of voyage time and excess distance travel by the ship before there is a heavy penalty on fuel consumption. Considering only a mean draft of 6 m and an average speed of 14 knots in the current paper, the optimal trim condition for the ferry is around -0.6 m (bow down), which reduces the resistance by 15% compared to the even keel condition. Positive trim causes the considerable increase of the total resistance consistently.

## INTRODUCTION

Shipping is the most important mode of international transportation for global supply chains, responsible for over ninety percent of global trade. In the past decade, the prices of bunker fuel have more than quadrupled, increasing on average 16% each year [1][2]. The rising fuel price has driven operating cost higher. There is ongoing pressure for ship owners and operators to reduce operating costs by improving fuel efficiency and invest in new fuel-efficient vessels.

In addition, there is continuous demand for more efficient shipping, in terms of cost, energy efficiency, environmental friendliness, timely delivery and economies of scale. The International Maritime Organization (IMO) has introduced new regulations under MARPOL to control emissions from ships, such as $SO_x$ and $NO_x$, which are directly proportional to fuel consumption. These regulations apply additional pressure for ship owners and operators to reduce fuel consumption.

 

These regulations currently apply only to ships traveling in Emission Control Areas (ECA). In North America, the ECA came into effect on August 1, 2012. All ships sailing within 200 nautical miles of the coast are required to use fuel oil with a maximum sulphur content of 1%. The SOx emission cap is 0.1% m/m on and after January 1, 2015 within the ECA. A global cap of 0.5% m/m will be in effect in 2020.

MARPOL Chapter 4, Annex VI introduced additional measures to reduce greenhouse gas (GHG) emissions on January 1, 2013. These include:

1. Energy Efficiency Design Index (EEDI), which is a mandatory technical measure for new ships.
2. Ship Energy Efficiency Management Plan (SEEMP), which is a mandatory technical measure for ships in service.
3. Energy Efficiency Operation Indicator (EEOI), which is a voluntary technical measure for ships in operation.

Each subsequent phases of EEDI will enter into effect every five years, reducing EEDI by an additional 10% each time.

## PROJECT OBJECTIVES AND SCOPE

NRC was commissioned by a ferry company to help them to reduce fuel consumption. NRC suggested a multi-phase approach to the problem, which includes:

Phase 1: Pilot Project
Data collection; conduct preliminary analysis to establish trends; explore key performance indicators (KPI) to establish baseline in Phase 2; and explore data products for performance management in Phase 3.

Phase 2: Performance Monitoring
Data monitoring; detailed analysis to establish baseline (e.g. speed profile, autopilot calibration etc.); propose data products for performance management; and discuss operational requirements with bridge crew and obtain feedback on proposed data products.

Phase 3: Performance Management
Produce tools to automatically compute KPIs after each voyage and perform cloud storage; introduce changes to improve efficiency (e.g. speed optimization, trim optimization etc.) and measure fuel savings; and explore dashboard tools for interactive feedback and predictive tools to aid bridge crew.

Phase 4: Operational Optimization
Expand implementation to the fleet; operational fleet benchmarking; further development on interactive feedback and predictive tools; provide tools for staff to access ship performance data anywhere; and continuous improvement.

A paper by Mak et al. in 2014 [3], described the work completed in Phase 1, which included preliminary data trends observed, key performance indicators computed, data products explored and exploratory tools developed for crews to gain insight into their vessel operation.

The current paper describes (1) further analysis of the operational data for speed optimization in calm sea states and (2) the development of a trim optimization software.

## INSTRUMENTATION

NRC proposed a set of measurements required to properly assess vessel performance and fuel efficiency. Table 1 lists the measurements identified.

**Table 1 Data for Assessment of Vessel Performance**

| Phase 1 Data Specified Data |
|---|
| Time (UTC) |
| Position (Latitude and Longitude) |
| Speed Over Ground |
| Course Over Ground |
| Heading |
| Speed Through Water |
| Rudder Angles (Port and Stbd) |
| Wind Speed |
| Wind Direction |
| Fuel Consumption |
| Shaft Speed (Port and Stbd) |
| Trim |
| 6 Degrees-of-Freedom (DOF) Motion |
| Loading Conditions |
| Shaft Torque |
| Draft |
| Stabilizer fin status and angle |
| Propeller pitch |
| Environmental conditions (e.g. wave) |

Two options were identified to collect this data – (1) acquiring it from the Voyage Data Recorder (VDR) or (2) developing a custom data logging software to monitor the parameters of interest. Due to operational concerns regarding acquisition of data from the VDR, NRC and our client elected to create custom data logger software.

The data logger software installed on the onboard computer collected data from five different sources – (1) Automatic Identification System (AIS), (2) Analog to Digital Converter, (3) Speed Log Sensor, (4) ETA Pilot, and (5) SMC IMU Motion Sensor. Table 2 shows the sources, NMEA protocol and interface of data collected.

 

Due to time constraints, the client requested to collect only data that did not require interface purchases from the manufacturers, which in some cases had a delivery time of over 7 weeks. Therefore, shaft torque, draft, stabilizer fin status and angle, propeller pitch and environmental conditions were not acquired in the pilot project; and loading conditions such as payload, displacement etc. were manually extracted from NAPA Loading Summary Report.

Figure 1 shows the setup onboard the vessel in an equipment room behind the bridge. All the instruments were self-contained in the pelican boxes. The instruments include a data acquisition computer, serial device servers, converters, optical isolation and uninterrupted power supply. Since this is a pilot project, the instruments were not installed and mount in wall enclosures. In the picture, a laptop was connected to configure and monitor the proper functioning of the data logger software. Figure 2 shows the instruments inside a pelican box connected to the various onboard systems.

Figure 1 Equipment onboard the vessel

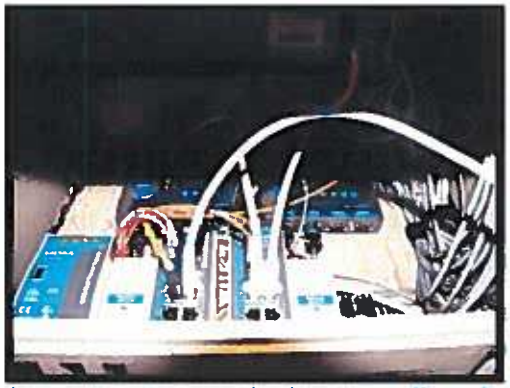

Figure 2 Instrument inside the pelican box

The data logger software acquired data continuously and stored them daily in files in the onboard computer. Once a week, the files were compressed and transferred through WiFi to an onshore computer for archiving.

## ANALYSIS OF SHIP DATA

The parser software first processed the raw measured data and output them into comma separated files, one for each source, for import into the analysis software. The analysis software synchronized the different data time series and resampled them, so the data points were equally spaced. Then, the data was inspected for correctness, completeness and proper formatting. Three weeks of data were analyzed.

For analysis purposes, each voyage was divided into three segments – maneuvering in Harbor A, maneuvering in Harbor B and travel in open water. This was because it is necessary to separate the performance data for harbor maneuvering and open water transit in order to assess speed profile, autopilot calibration, trim optimization etc. The voyages were further divided into two routes. The two routes were – (a) Normal route for calm sea states (Figure 3) and (b) Irregular route probably for heavier sea states (Figure 4).

Figure 3 Normal route

Figure 4 Irregular route (Aug 30, 2013)

 

Without the environmental data from wave buoys in the vicinity, the analysis was limited to the calm sea state runs. NRC assessed the SmartBay wave buoy in Port Aux Basque but it was found that the buoy was too close to shore. The wave measurement was sheltered and was not representative of the sea state in open water. The use of hindcast data is being investigated and will be presented in the future. The following process was taken to identify the calm sea state runs, and their optimal trip duration, optimal distance and optimal constant speed to minimize fuel consumption.

First, with the knowledge from our client that the captains of the ferry would take longer, indirect routes (Irregular routes) to avoid heavy seas, we consider calm seas runs to be voyages that closely follow a straight line drawn between the two harbors. The distance travelled of each of these voyages was within 5 km of the distance of the straight line.

Second, we plotted "Fuel / Displacement versus Trip Duration" for all the calm sea state runs and fit a third order polynomial through the data to determine the optimal trip duration that uses the least amount of fuel per unit of displacement (Figure 5).

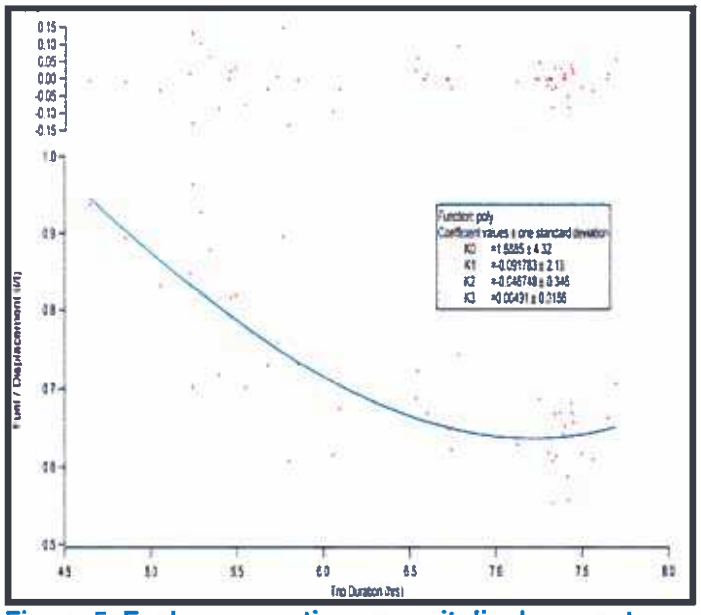


**Figure 5. Fuel consumption per unit displacement versus voyage duration**

## RESULTS AND DISCUSSION OF SHIP DATA

As can be seen from the fitted curve in Figure 5, trip durations around 7 hours use the least amount of fuel. There is a large deviation of trip duration, ranging from 4.5 hours to 8 hours. From this plot, it illustrated that high speed voyages used a lot more fuel. The faster the voyage (or the shorter voyage duration), the more fuel was burned. At the opposite end, we see also that more fuel is burned if the trip duration is longer than 7.5 hours. The vessel travelling slowly is burning less fuel per unit time but the voyage takes much more time, resulting in an overall increase in fuel consumption.

These effects are demonstrated in the contour plot in Figure 6. It shows voyage duration versus percentage of excess distance travel from the straight line route between the two harbors, and fuel consumption in litres on the z-axis. As the green portion of the graph shows, the least amount of fuel is used if the excess distance travelled and the voyage time are both optimized. High speed voyages and longer distance travel will result in high fuel usage as indicated in the red zones.

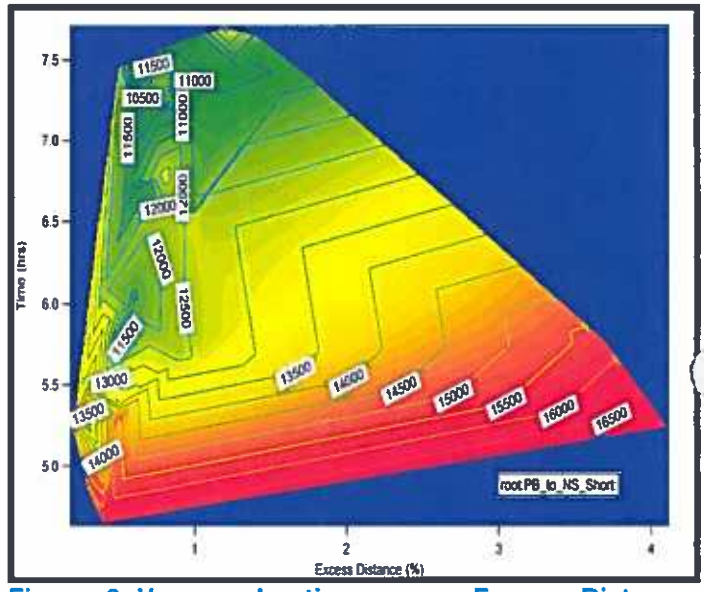


**Figure 6 Voyage duration versus Excess Distance Travel from a straight line between the two harbors (Calm Sea State Voyages)**

Figure 7 shows a contour plot of voyage duration versus percentage of excess distance travel from the straight line route between the two harbors, with fuel consumption on the z-axis, for all the voyages including calm sea state runs (normal routes) and high sea state runs (irregular routes).

The area bounded by the black dotted rectangle denotes the calm sea state voyages shown in Figure 6. The green area in the figure shows that there is a lot of leeway in terms of voyage time and excess distance travel by the ship before there is a heavy penalty on fuel consumption, shown in the red areas.

 

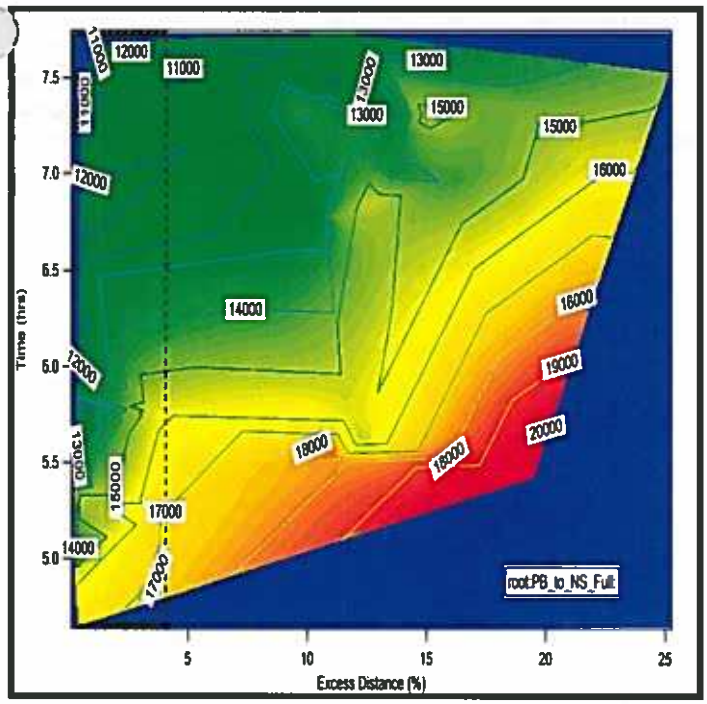


**Figure 7. Voyage duration versus Excess Distance Travel from a straight line between the two harbors (All Voyages)**

Figure 8 shows a plot of fuel consumption per unit displacement versus standard deviation from optimum speed, with voyage duration about 7 hours.

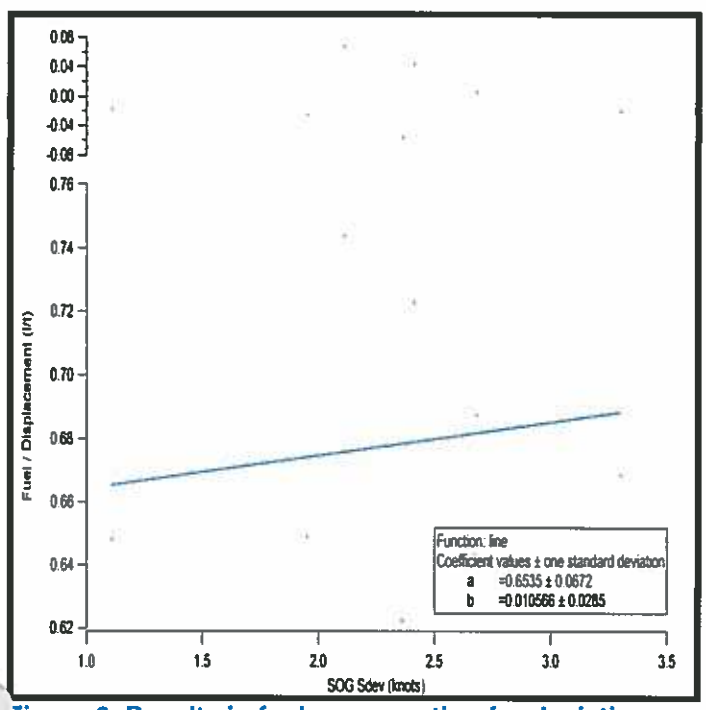


**Figure 8. Penalty in fuel consumption for deviation from optimal constant speed**

Two ships can travel the same distance and have the same voyage time. However, the ship that maintains a constant speed will use less fuel. A ship that varies speed throughout the voyage will consume more fuel. This effect is shown in Figure 8. A line is fitted through 7 voyages that met two criteria - (1) deviation of voyage distance less than 5 km from the straight line distance between the two harbours; and (2) voyage time within 15 minutes of each other. Figure 8 shows that for every knot of speed deviation from optimal constant speed, there is a penalty in fuel consumption (indicated by the slope of the fitted line).

## TRIM OPTIMIZATION

Trim is one of the key parameters that affect fuel consumption. Others include ship speed, draft, wake fraction, propeller efficiency etc. Trim condition is examined with consideration of the operational requirements. Speed and draft (or displacement) have a limited range considering the operating route, shipping time and payload. For the preliminary development of trim optimization, the mean draft was set to 6 m and speed was fixed at 14 knots. These constraints will be removed in the future when we conduct a comprehensive study.

To assess the trim effect on fuel consumption, the full-scale ship resistance is estimated by CFD software. To simplify the problem and minimize the computational cost, rudder, propellers and small appendages are not included in this study. The predicted values in different trim conditions are compared to determine the best trim condition for fuel saving.

## NUMERICAL MODEL FOR TRIM OPTIMIZATION

Star-CCM+ is used to simulate the flow around the ship and predict the hull resistance. The detail formulations and the numerical methodologies for CFD are well documented in many literatures. So, only the main features and applied numerical schemes are described in this paper. RANS (Reynolds-averaged Navier–Stokes) model with K-omega SST (Shear Stress Transport) turbulence is used in this study considering that lots of CFD studies for ship resistance adopted K-Omega model [4]. In order to consider the free surface effect related with wave making resistance, VOF (Volume of Fluid) method is also used. The simulation procedure and numerical scheme are based on the ITTC practical guideline [4].

## GRID GENERATION AND BOUNDARY CONDITIONS

Trimmed mesh is generated considering computational cost and accuracy. The prismatic layers are attached to the ship surface to capture the near wall flow accurately. The ship dimension and numerical domain size are shown

 

in Tables 2 and 3 respectively. The generated surface grid is shown in Figure 9. The applied boundary condition and a typical section of volume mesh is shown in Figure 10.

**Table 2 Main dimension of the ferry**

| | |
|---|---|
| Length (m) | 199.50 |
| Beam (m) | 26.70 |
| Draft (m) | 6.00 |
| Block Coeff. | 0.5653 |

**Table 3 CFD computational domain**

| | Min. | Max. | Note |
|---|---|---|---|
| X | -2 x Lpp | 2.5 x Lpp | A.P. is set to 0 |
| Y | 0 | 1 x Lpp | Centre line is set to 0 |
| Z | -1 x Lpp | 1 x Lpp | Hull base line is set to 0 |

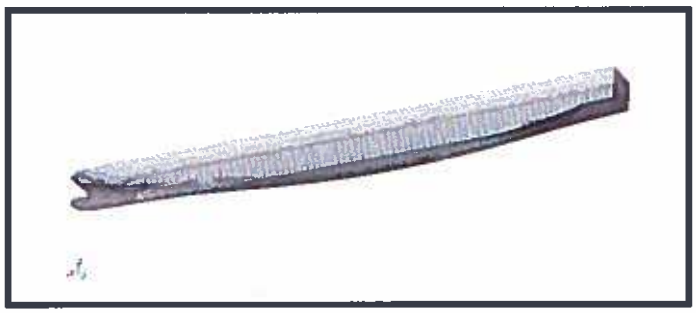

**Figure 9 Typical surface mesh for CFD analysis**

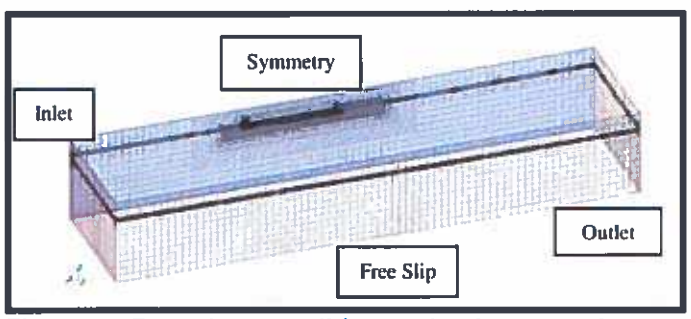


**Figure 10 Boundary condition and volume mesh**

### Uncertainty Assessment

Basic uncertainty analysis is conducted using total resistance from three different grid sizes as shown in Table 3. For the convergence assessment, even keel condition is selected. The test condition of convergence assessment is summarized in Table 4. The detail assessment procedure is described in ITTC Recommended Practices [5]. Based on the ITTC recommendation, main result of convergence assessment is summarized to Table 5. The convergence ratio, $R_K$ is around 0.7, which corresponds to the monotonic convergence case. As a result, applying generalized Richardson's extrapolation, the error $\delta_{RE_{k1}}$ can be approximated to 1.5 x$10^{-5}$.

**Table 4 Grid size and result for convergence assessment**

| Grid Size | No. of cell | Reference Mesh Size [m] | Total Resistance Coefficient |
|---|---|---|---|
| Fine | 4.3 x $10^6$ | 0.35 | 2.42 x $10^{-4}$ |
| Medium | 2.0 x $10^6$ | 0.50 | 2.48 x $10^{-4}$ |
| Coarse | 1.2 x $10^6$ | 0.71 | 2.56 x $10^{-4}$ |

**Table 5 Summary of convergence assessment**

| $\varepsilon_{k_{21}}$ | $\varepsilon_{k_{32}}$ | $r_k$ | $R_k$ | $p_k$ | $\delta_{RE_{k1}}$ |
|---|---|---|---|---|---|
| 6.02 x $10^{-6}$ | 8.46 x $10^{-6}$ | 1.40 | 1.41 | 1.01 | 1.5 x $10^{-6}$ |

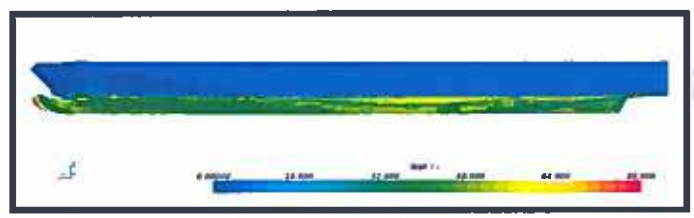

**Figure 11 Typical wall Y+ value**

## RESISTANCE PREDICTION

Considering the mean draft of the ship, 5 different trim conditions are evaluated. Calculation result as well as additional information such as volumetric displacement is summarized in
Table 6. The calculated resistance is normalized to resistance coefficient using the following equation. As shown in
Table 6, total resistance ($C_T$) is divided into the pressure ($C_P$) and frictional ($C_F$) resistance to analyze the main resistance factor.

$$C = \frac{\text{Resistance}}{2\rho S V^2}$$

where, ρ is water density, S is wetted surface area and V is forward speed.

Figure 12 shows the calculated resistance coefficient corresponding ship trim. As shown in the figure, it is noted

 

that considerable resistance change is observed. Comparing three coefficient curves, pressure resistance component is the more dominant compared with frictional term.

In addition, pressure resistance can be divided into viscous pressure resistance (also called as form drag) and wave making resistance. It is hard to separate those two components clearly from CFD result. So wave profile is plotted and compared. Qualitatively, wave profile can represent wave making resistance. Figure 13 and 14 shows the bow and stern wave profile corresponding different trim condition.

From Figure 13 and 14, it is noted that positive trim produces a higher bow and stern wave compared with even keel and negative trim. Especially, the stern wave is supposed to give more significant impact to the resistance changes compared with the bow wave. In Figure 14, 1.2 m of peak wave profile is observed compared with 0.4 m for even keel case. It is supposed that wave making resistance gives the most significant impact on the total resistance change.

**Table 6 CFD prediction summary for trim optimization**

| Trim* [m] | -1.04 | -0.69 | -0.35 | 0.00 | 0.35 | 0.69 | 1.04 |
|---|---|---|---|---|---|---|---|
| Disp. Vol. [$x10^3$ $m^3$] | 22.0 | 22.0 | 22.1 | 22.2 | 22.3 | 22.4 | 22.6 |
| Wetted Surface Area [$m^2$] | 5874 | 5905 | 5926 | 5893 | 5951 | 5958 | 5968 |
| $C_P$ ( $x\ 10^{-5}$ ) | 2.16 | 0.66 | 0.65 | 4.48 | 6.96 | 8.27 | 10.6 |
| $C_F$ ( $x\ 10^{-4}$ ) | 2.15 | 2.08 | 2.13 | 2.04 | 2.12 | 2.16 | 2.17 |
| $C_T$ ( $x\ 10^{-4}$ ) | 2.37 | 2.14 | 2.20 | 2.48 | 2.81 | 2.99 | 3.23 |

(* Trim by stern is plus value)

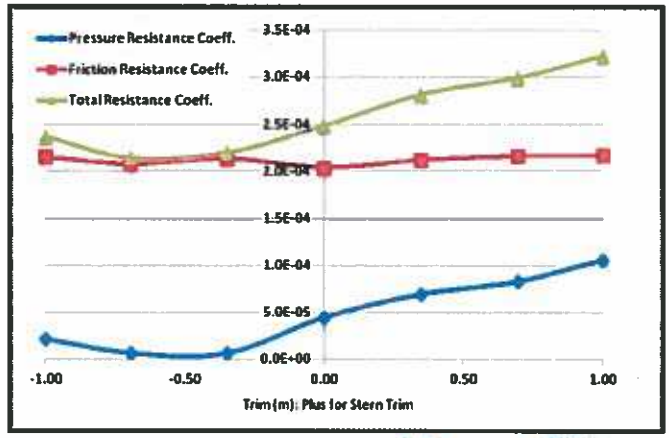


Figure 12 Comparison of resistance coefficient

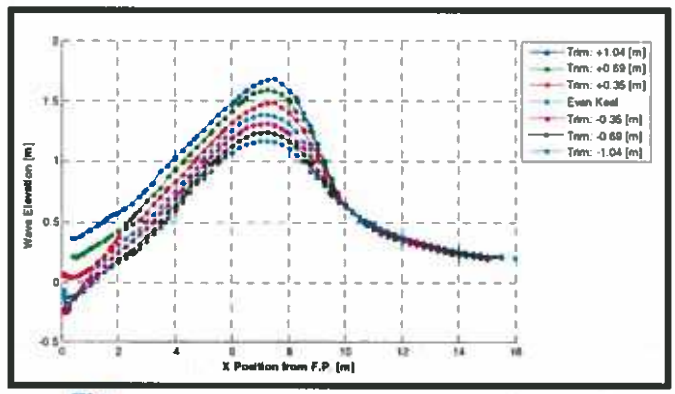


Figure 13 Comparison of bow wave profile

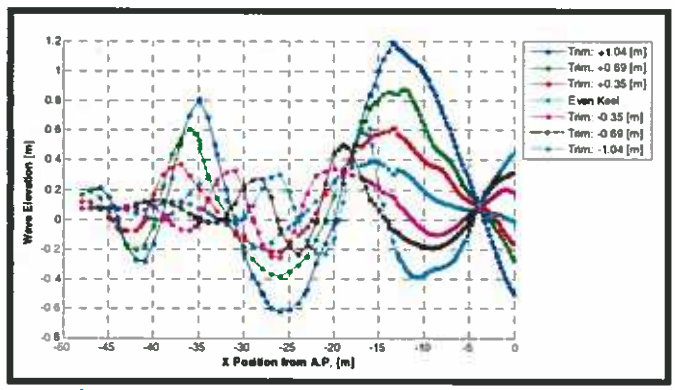


Figure 14 Comparison of stern Wave Profile

## DISCUSSION OF TRIM OPTIMIZATION

Figure 16 shows resistance changes corresponding to different trim conditions. As shown in the figure, optimal trim condition for the ferry is around -0.6 m. A proper negative trim (trim by bow) can achieve the significant resistance reduction about 15% compared with the even keel condition.

 

Positive trim causes the considerable increase of the total resistance consistently. For fuel saving, positive trim has a significant disadvantage in ship resistance. However, negative trim may cause a loss of maneuverability and propeller cavitation which can impact on the operation safety. A comprehensive study including other factors (e.g. cavitation and maneuverability) related with trim is necessary to confirm the optimized trim condition given the operational requirements. Moreover, speed effect and draft change omitted in this paper should be investigated to assess the optimal condition of the ship for fuel savings.

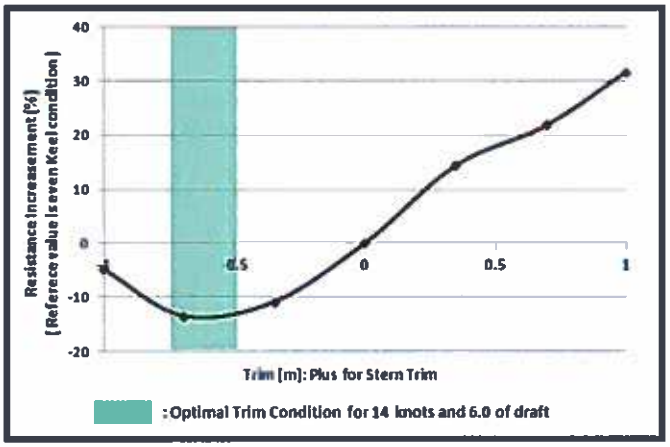


Figure 16 Optimal trim condition

## CONCLUSIONS

1. From the operational data, trip durations around 7 hours use the least amount of fuel. High speed voyages used a lot more fuel. Slow speed voyages burned less fuel per unit time but the voyage took longer, resulting in an overall increase in fuel consumption.

2. The least amount of fuel is used when the excess distance travelled is minimized and the voyage time is optimized.

3. There is a lot of leeway in terms of voyage time and excess distance travel by the ship before there is a heavy penalty on fuel consumption.

4. Two ships can travel the same distance and have the same voyage time. However, the ship that maintains a constant speed will use less fuel. A ship that varies speed throughout the voyage will consume more fuel.

5. There is considerable change in calculated resistance coefficient when trim is varied. Pressure resistance component is the more dominant compared with frictional term. It is hard to separate viscous pressure resistance and wave making resistance quantitatively from CFD result.

6. Wave profile can represent wave making resistance. Bow and stern wave profile were plotted for comparison. The results show that positive trim produces a higher bow and stern wave compared with even keel and negative trim. Stern wave is supposed to give more significant impact to the resistance changes compared with the bow wave.

7. Optimal trim condition of the ferry is around -0.6 m (trim by bow). A proper negative trim an achieve the significant resistance reduction about 15% compared with the even keel condition. Positive trim causes the considerable increase of the total resistance consistently.

## RECOMMENDATIONS

1. A complete implementation of the remaining data (i.e. environment condition, propeller pitch, trim and draft etc.) is required on the ferry to better understand the impact of the various variables on fuel consumption.

2. A comprehensive study including other factors (e.g. cavitation and maneuverability) related with trim is necessary to confirm the optimized trim condition for the given operational requirements.

3. Speed effect and draft change omitted in this paper should be evaluated to assess the optimal condition of the ship for fuel savings.

## REFERENCES


1. Bailou, P.J. (2013), "Ship Energy Efficiency Management Requires a Total Solution Approach", Marine Technology Society Journal, pp 83-95.

2. Paris, C. (2013), "Shippers Struggle With Overcapacity, Sinking Rates", The Wall Street Journal, http://online.wsj.com/news/articles/SB10001424127887323798104578454812392168852, Updated May 2, 2013.

3. Mak, L., Kuczora, A., Sullivan, M. and Millan, J. (2014), "Ship Performance Monitoring and Analysis to Improve Fuel Efficiency", Proceeding of Oceans'14 MTS/IEEE Conference, Sept 14-19, St. John's, NL, Canada.


 

4. ITTC, 2011, "Practical Guidelines for Ship CFD Application", No. 7.5-03-02-03

5. ITTC, 1999, "Uncertainty analysis in CFD, Guidelines for RANS codes", No. 7.5-03-01-02

 