Jurnal Teknologi

Full paper

Evaluation of Service Performances of Liquefied Natural Gas Carriers in Actual Seas

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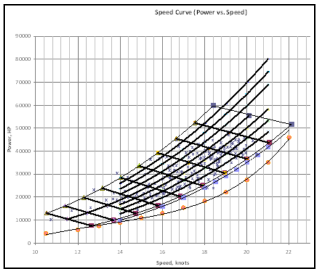
Article history

Received :1 June 204
Received in revised form :
2 June 2014
Accepted :6 June 2014

Graphical abstract



Abstract

Ship performance in actual seas represents the true performance of the ship throughout the service life and is affected by the combination of various conditions i.e. environments, loading patterns and ship conditions. Environmental conditions of wind, wave, swell and ocean current are chaotic and stochastic in nature. Loading condition may vary in draft, trim and motions in each voyage. Ship condition is susceptible to hull and propeller fouled over years. This paper provides insight into the service performance of Liquefied Natural Gas Carriers (LNGC) in actual seas derived from post-mortem on years of voyage's noon report collections. Evaluation method of service performance will be proposed and benefits that can be gained from such analysis will be discussed.

Keywords: Service performance; speed loss; added resistance; ship routeing; LNG carrier

■1.0 INTRODUCTION

Performance of Liquefied Natural Gas Carriers (LNGC) can be manifested into two stages i.e. performance in calm water and in actual seas. Performance in calm water has gained more attention, extensive research, design optimization and scale model testing. Results outcome of model testing are finalized as a ship performance in calm water and it is used to determine the guarantee speed of the ship. The speed will be adjusted accordingly by the designer to meet the Purchaser's requirements by the inclusion of margins i.e. sea, engine operating, calm water powering and propeller margins. As part of contractual obligations, speed trials at full scale are performed in order to validate and prove the guarantee speed. Thus, the guarantee speed as stipulated in the shipbuilding contract is merely an attained speed corresponding to the power requirements in calm water condition with an addition of powering and sea margins. Even though this is a long practice of the shipbuilding industry, it does not guarantee the ship will performed in similar manner throughout the service life.

Performance in actual seas represents the true performance of the ship throughout the service life and is affected by the combination of various conditions i.e. environments, loading patterns and ship conditions. Environmental conditions such as wind, wave, swell and ocean current are chaotic and stochastic system in nature. Loading pattern may vary in draft, trim and motions in each voyage. Ship condition is susceptible to hull and propeller fouled over years. Combination of these conditions affects the overall performance of the ship. Given by complexity and non-linearity of each factors, analysis of ship performance in a seaway is a difficult problem.

Both stages are equally important. Performance in calm water set the performance benchmark in ideal condition. Improving performance in calm water will improve performance in actual seas accordingly although this can only be improvised at conceptual design stage. Analyzing the nature of ship behaviours in seaway provides deeper understanding of ship and environment interactions. It is always privileged to gain such knowledge as it will provide stakeholders in ship design and operation a clear perspective of ship resistance, effect of hull and propeller roughness to the fuel consumption, speed loss in seaway, effect of displacement and trim to the ship performance, weather and voyage information, sea margin and optimal ship routeing.

■2.0 DATA MANAGEMENT AND SHIP INFORMATION

2.1 Data Collection and Management

Systematic noon reporting was exercised since year 2004 and it was estimated that more than 20,000 data were collected, managed and analyzed. It shall be noted that the noon reports are the collection of daily voyage and log data taken and reported daily by ship's crew in every transit. The log primarily consists of, but not necessary limited to, navigation data, weather observation and engine performance. Since the adoption of noon reporting is solely for the fleet management purpose, it may be assumed that the reporting may contains inconsistency, inaccuracy, approximation, estimation or error in input data that may resulted from human error, bias or poor judgement. This deficiency cannot be avoided since the collection effort involved a thousand of peoples managing a thousand of data. However, collection of sufficient number of data will expose consistency and ergodicity, while outliers can be pinpointed and cast out accordingly. Engineering sense and theoretical validation has given further guidance when dealing with these data.

The ship performance in actual seas is being analysed and established from these data collections. This is somehow has follows the same step taken by previous researches notably James (1957), Aertsen (1969), Babbedge (1975), Townsin and Kwon (1982), Townsin *et al.* (1993) and Kwon (2008). In their works, they have produced generic empirical formulae or approximation that may be used for any other ships, normally comes with corrections for encountering angle case or ship type. This approximation may provides good indication on ship performance in various sea conditions and especially useful for preliminary design. For a more refine application, an approximation may not always produce a good result, at least in term of accuracy. A unique set of ship performance shall be used then, which in any measures shall provide the best indicator of the true performance of ship in a seaway. Any inaccuracies from the calculation may due to the inaccurate or insufficient set of data, rather than from the method or approach itself.

2.2 Ship Information

As for this paper, MISC Berhad's LNG carriers from "Tenaga" class are selected as study case. The selection is made based on trading route, loading pattern and data availability factors. Unless specified otherwise, most of analysis and discussion parts are within Malaysia-Far East LNGC's routes context.

Presently, MISC Berhad is among the largest single owner-operator of LNG carriers. Tenaga class consists of five (5) LNG carriers and is the oldest fleet with average fleet age of 30 years old. She was built in early 80's at Societe Metallurgique Et Navale Dunkerque-Norman and Chantiers De Nord Industrielle Marseile in France. Main particulars of Tenaga class are summarised in Table 1.

■3.0 RESULTS AND DISCUSSIONS

3.1 Route Tracking

In most of her lifetime, LNG carrier Tenaga class was chartered to transport LNG cargoes from loading terminal in Bintulu, Sarawak to offloading terminals in Far East region i.e. Taiwan, Japan or South Korea. Occasionally, she was also operated in other regions e.g. Egypt or USA.

The laden voyage is normally taken about 3 to 7 days depending on voyage distance and attained ship speed. Similar duration would be expected for the ballast voyage case. Due to typical LNG business modus operandi i.e. time-charter, Tenaga class would return to a similar loading terminal on ballast voyage, after successful delivery of cargo to unloading terminal. The ratio between laden mode and ballast mode are 1:1 or 50%:50%. As she was installed with membrane type cargo containment system; there is restriction on the cargo loading due to sloshing issue. In most cases, the cargo containments are filling-up at almost full or it can be considered as consistent in every laden voyage. The draughts and changing in draughts are expected to be consistent for each voyage, or at least for laden case. This may not always be the case for the ballast voyage, owed much to the minimum cargo filling and voyage planning. In this paper, most of the examples are for the laden case, unless specified otherwise.

Typical voyages patterns of Tenaga class are in facts should provide several advantages to ship owner or operator in managing or planning the voyage. Rather the optimal routeing opportunity has not been fully utilized as in the all cases the ship master would prefer to use standard path or similar track, for both laden and ballast cases.

Figure 1 shows track plotting of all MISC's LNGC fleet including Tenaga class. Regardless of details explanation, it is very obvious that most voyages' longitude or latitude position plot is fall on the same line and inadvertently forming an "ocean highway". The connection of plots is representing the complete ship's route tracking based on over than 15,000 voyage data. In detail close-up for weather zone E22 case, as per Figure 2, the monthly-based plotting proved a similar outcome. Outliers on the plotting graph mostly represent ship's track deviating from standard route due to safety reason, storm or typhoon avoidance and laying-up at anchorage zone.

From these evidences, it can be concluded that the previous voyage plan or execution of Tenaga class is merely based on standard route practice, with almost no alternative routes. This kind of practice has its own advantages and disadvantages. The real benefits from the optimal ship routeing practice are not being fully acquired but consistent route selections may provide more confidents in term of voyage management, safety and security.

Table 1 Main particulars of tenaga class

Type / Class	**Steam Ship / ABS**
Length Overall	280.62 m
Length B.P	266.00 m
Breadth (moulded)	41.60 m
Depth (moulded)	27.50 m
Draught at Laden	Abt. 11.70 m
Draught at Ballast	Abt. 10.50 m
Service Speed at Laden Draught	19.50 knots (at NCR, 21% Sea Margin)
Displacement	101,332 MT
Windage	Abt. 5919 m^2 (Lateral) Abt. 1600 m^2 (Longitudinal)
Block Coefficient, C_B	0.736
VCG at Laden	14.78 m
Propeller (Pitch Ratio)	7.70 m Dia. x 5 Blades x (0.9682)
MCR / NCR	33556 / 31319 kW
RPM at MCR	108 rpm
Cargo Capacity	130,000 m^3

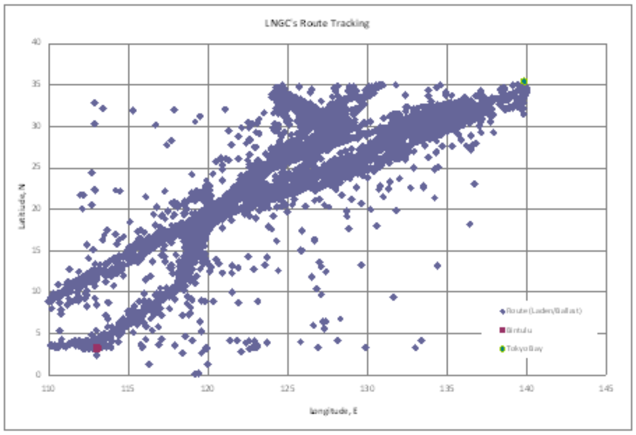


Figure 1 Route tracking in East Asia region

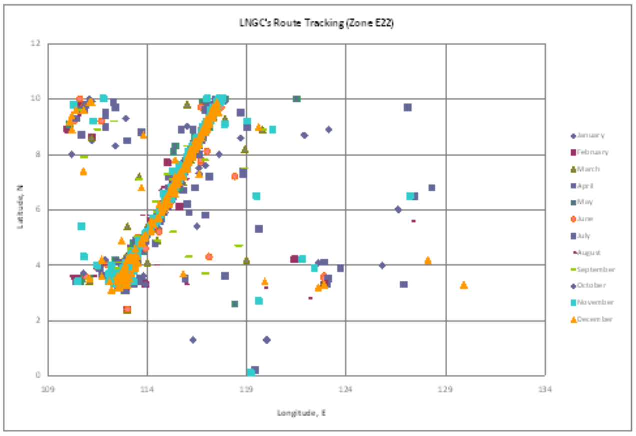


Figure 2 Monthly route tracking in weather zone E22

3.2 Weather Observation Record

In each of noon report, daily weather observations from bridge are recorded. As for Tenaga class case, the weather was described in Beaufort scale and true wind direction. This simplified version is practical though it is not really representing the weather or environment conditions at that particular time. Again, it shall be reminded that the original noon report objective may not include full weather reports. It is suffice with converted wind speed and direction reading from anemometer. The only obvious set-back is that the information was recorded once or twice per day; this is never precisely describing the weather for that particular day.

Shall we consider more comprehensive weather representations, it shall be noted that most of merchant ships, even if sophistically designed, were fitted with no wave or motion sensors. Wave information may be recorded from visual observation i.e. wave height, wave direction and wave period, but it suffered lack of accuracy. Also, without assistance from sensor readings, it is almost impossible to observe wave at night time, even if there is practical reason to do so.

This topic is significance due to the potential of daily weather logs. One of the contributions can be seen in Voluntary Observing Ship (VOS) scheme embarked by World Meteorological Organization (WMO). The VOS scheme is an international program that recruits ships around the world to take record and transmit weather observations whilst at sea. Another important contribution can be seen at the work of Hogben and Lumb (1967) and Hogben *et al.* (1986) that contain statistical distributions based on limited visual wave data for 50 and 104 areas of the ocean respectively.

Another reason to elaborate on meteorological aspects of noon report is to justify and provide confidence in data collections for this study. Shall the data be validated against comprehensive meteorological data e.g. established weather collection by meteorological agency; it can provide required level of data acceptance and significance. In conjunction, it may be concluded that the other voyage records from noon reports are also valid and in consistent with the environments accordingly. For instance, the attained speed, fuel consumption or engine output is in conjunction with the recorded weather data for that particular time. Similarly, the ocean current is reflected in the speed over ground (SOG) or speed through water (STW) records.

As for this purpose, wave and wind database produced by National Maritime Research Institute (NMRI) will be used as a comparison. Data in the database comprises two categories i.e. scatter diagrams on sea areas in the North Pacific and wave height distribution tables for sea areas worldwide. The scatter diagrams in the North Pacific are further classified into three categories, ship reports, hind casting and buoy measurement. The data of ship reports, hind casting and buoy measurement were collected in year 1974-1988, 1980-1989 and 1978-1989 respectively. Figure 3 shows the division of sea areas according to NMRI standard.

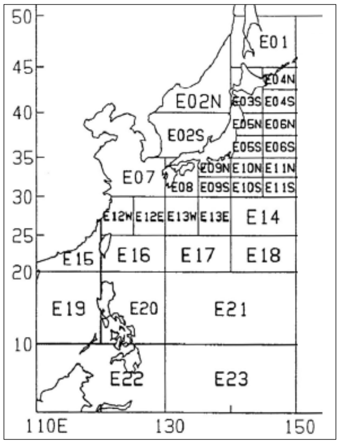
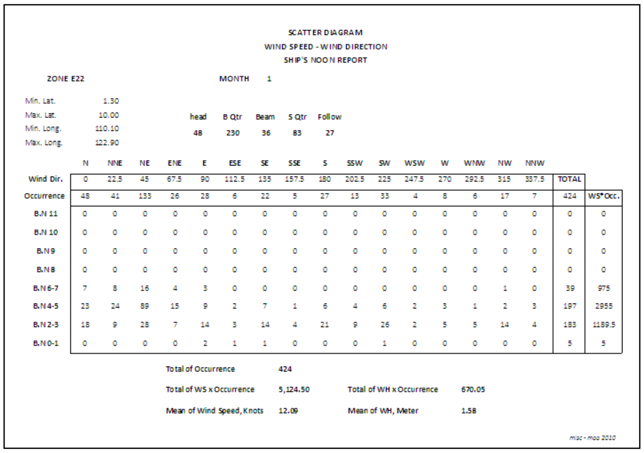


Figure 3 Division of sea zones (NMRI, 2006)

In this exercise, it was estimated over than 20,000 weather observation data were collected, managed and analyzed. These data are divided into total of ten (10) respective sea areas or weather zones in accordance with NMRI database. The selection of ten (10) weather zones is decided following the Bintulu to Far East route study cases. The data from noon reports are originally registered as the true wave direction and Beaufort number formats. For example “Sx3” represents Beaufort 3 wind that coming from south or 0º heading. The wind speed was a velocity equivalent at a standard height of 10 meters above sea water level. All data are managed, processed, analyzed and tabulated as scatter diagram; sample is shown in Figure 4. The wind speed and significant wave height relationship formulation used in this study follow closely the averaging value of the standard Beaufort scale of wind as provided by WMO (2011), as summarised in Table 2.



SCATTER DIAGRAM
WIND SPEED - WIND DIRECTION
SHIP'S NOON REPORT

ZONE E22 MONTH 1

Min. Lat.	1.30
Max. Lat.	10.00
Min. Long.	110.10
Max. Long.	122.90

head	B Qtr	Beam	S Qtr	Follow
48	230	36	83	27

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW		
Wind Dir.	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	TOTAL	
Occurrence	48	41	133	26	28	6	22	5	27	13	33	4	8	6	17	7	424	WS*Occ.
B.N 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B.N 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B.N 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B.N 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
B.N 6-7	7	8	16	4	3	0	0	0	0	0	0	0	0	0	1	0	39	975
B.N 4-5	23	24	89	15	9	2	7	1	6	4	6	2	3	1	2	3	197	2955
B.N 2-3	18	9	28	7	14	3	14	4	21	9	26	2	5	5	14	4	183	1189.5
B.N 0-1	0	0	0	0	2	1	1	0	0	0	1	0	0	0	0	0	5	5

Total of Occurrence	424		
Total of WS x Occurrence	5,124.50	Total of WH x Occurrence	670.05
Mean of Wind Speed, Knots	12.09	Mean of WH, Meter	1.58

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Figure 4 Sample of scatter diagram

Table 2 Beaufort scale of wind (WMO, 2011)

Beaufort Number	Description	Wind Speed (knots)	Wave Height (m)
0	Calm	< 1	0
1	Light Air	1 - 3	0.1
2	Light Breeze	4 - 6	0.2 - 0.3
3	Gentle Breeze	7 - 10	0.6 - 1
4	Moderate Breeze	11 - 16	1 - 1.5
5	Fresh Breeze	17 - 21	2 - 2.5
6	Strong Breeze	22 - 27	3 - 4
7	Near Gale	28 - 33	4 - 5.5
8	Gale	34 - 40	5.5 - 7.5
9	Strong Gale	41 - 47	7 - 10

Analyse data from scatter diagram of all zones are then compared and validated against NMRI database; based on month, zone and source of data. For instance, Figure 5 and Figure 6 show the example of comparison of significant wave height (SWH) and mean wind speed (MWS) of Zone E22 and E16 respectively. Legend "MISC" represent analysed data from Tenaga class; "NMRI 1" is collection from ship's report; while "NMRI 2" is a hind casting data. In general, both graphs show the close agreement in term of value, pattern and trend. Slight disagreement may be explained; sufficient number of data from NMRI are actually well scattered around of each respective weather zone, while in Tenaga class case, the weather information are quite concentrated on the same route. Nevertheless, the close agreement and consistency is shown between Tenaga class and NMRI data.

The higher values are between September and March; while lower values are between April and August. This may be deduced as results from storm and typhoon seasons in East Pacific Area. In year 2009 alone, a total of 22 storms and 14 typhoons are recorded in this region, mostly occurred between July and December. The same analysis is replicate for the other weather zones and also shows similar graph outcome and resemblance. This is, on a more important note, has proved that the noon report data from Tenaga class can be classified as trustworthy, reliable and statistically significant.

From ship routeing point of view, Figure 5 and Figure 6 are both statistically represent local weather behaviours in Bintulu-Far East route. In term of average value, each month is indeed has shown different value. Hypothetically, two suppositions can be made. First, the influence of monthly weather on ship performance is obvious and secondly, standard route practice throughout the year shall not be accepted as an optimal ship routeing. Optimal weather routeing or seasonal routeing are perceived as a better choice in voyage planning and management.

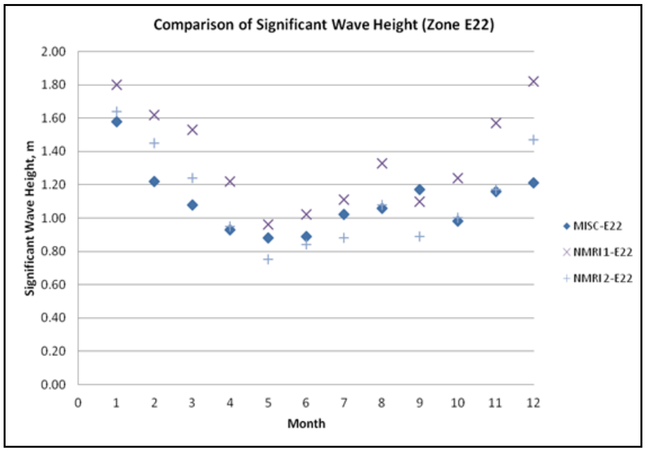


Figure 5 Comparison of significant wave height in zone E22

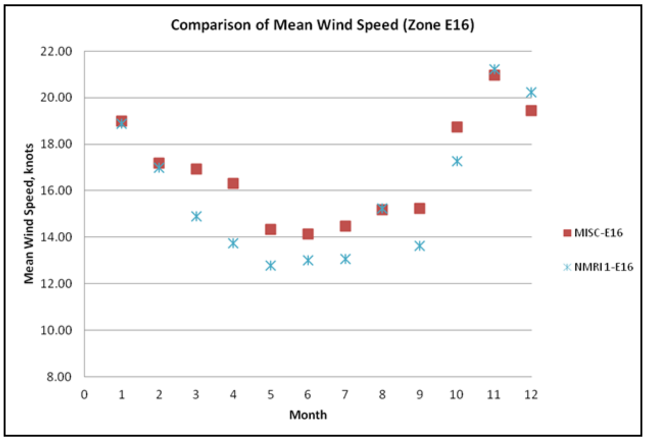


Figure 6 Comparison of mean wind speed in Zone E16

3.3 Speed Profile

Figure 7 and 8 show the speed and engine power output distribution for laden case, both are divided by incident wave case i.e. head, beam, following, bow quartering and stern quartering seas. In general, the speed profile shows negative skewed distribution with an average speed of 17.5 knots, while power output is normal distributed with an average power of 31,600 horsepower.

In Figure 7, general distribution of speed resulted from various factors mainly voluntary and involuntary speed reduction actions. The distribution skewness may be explained from the charter speed and tactical points. In each of her voyage, Tenaga class was obliged to honors Charter Party performance clause i.e. speed performance in fair-weather. Thus, higher occurrences are scattered around service speed of 19.5 knots region. On the lower speed case, this is more on a tactical part of voyage e.g. speed reductions in order to arrive just-in-time at terminal destination or slow steaming while awaiting storm path clearance.

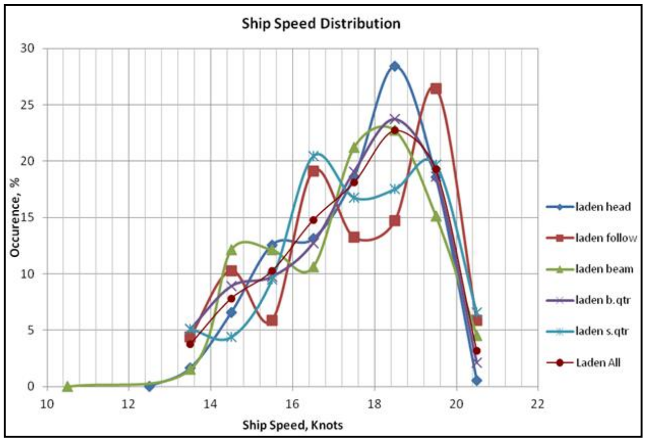


Figure 7 Speed profile for laden case

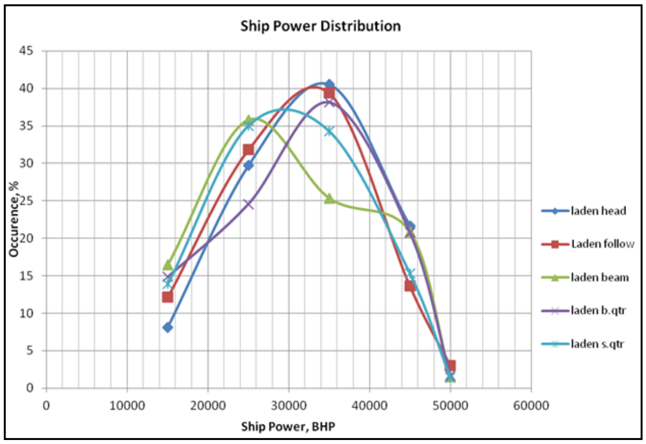


Figure 8 Engine output profile for laden case

Though speed and engine power output are mathematically related, both graphs shall be better considered as an independent property. An effort to explain the trend of Figure 7 as a direct outcome from Figure 8 will produce inconsistency explanation from theoretical point of view. For example, higher occurrences in speed profile are not necessarily a direct result from higher occurrence in engine power output, since is there are so many other contribution factors. The speed and power relationship however will be further explained and discussed in subsequence topics.

3.4 Calm Water Resistance

Figure 9 shows the calm water resistance curve of Tenaga class; consists of both model test results and prediction calculations. In this exercise, Holtrop-Mennen and Series 60 prediction methods are plotted as comparisons. Scale model resistance tests are carried out in Marine Technology Center (MTC), Universiti Teknologi Malaysia (UTM). It shall be noted that both prediction methods show good agreement with model test results. However details on model test or prediction methods will not be discuss or elaborate in this paper. The importance of this brief discussion is to establish benchmark for ship performance i.e. calm water resistance curve which will be used in subsequence topic.

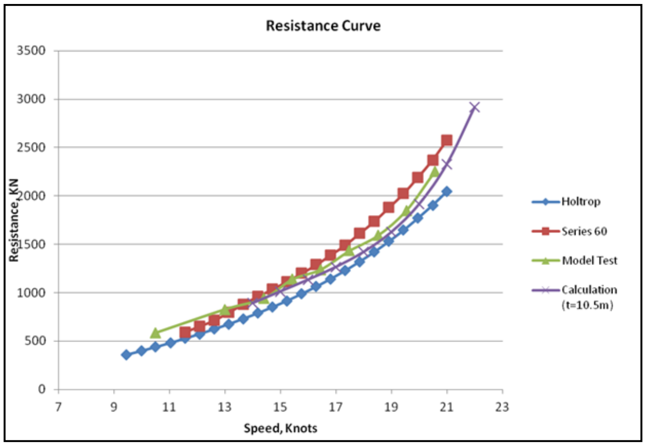


Figure 9 Calm water resistance

3.5 Ship Performance in Actual Seas

By using the advantage of empirical formulation, the service performance of Tenaga class in actual seas are analysed and formularised. The distinction between this analysis and approximation methods is on the data that are used are actual performance and are specific for Tenaga class. The real benefit from this approach is the accuracy of the calculation results itself, shall we consider using this practical approach in optimal ship routeing calculation process. Whilst many other studies notably by Chen (1978), Motte (1981), Avgouleas (2008), Tsujimoto *et al.* (2009) and etc. used the elegance mathematic formulation to predict the ship response in seaways, this may not always produce an accurate results especially in oblique, beam and following seas.

Although the proposed service performance model is a simplification, the developments are actually based on ship resistance and powering theory. The models are also validated against various theoretical formulae and empirical approximations from the work of Townsin and Kwon (1982), Townsin *et al.* (1993), Kwon (2008) and etc as summarised in Table 4. More importantly the ship service response is also validated with the actual data from past complete voyage. The validation is done through ship routeing simulation, as if it was performed prior to the actual voyage. The model formulation will not be discussed in this paper. Further details can be referred to the work of Azuwan (2013).

In brief, all data from noon reports are segregated into five encountering angle or heading group i.e. head, beam, following, bow quartering and stern quartering seas. By using the unique set of data of each group, speed curve is plotted. The speed curve represents the power requirement for each respective speed. The curves are also representing different set of performance; set of degradation curve or “weather curve”. Figure 12 shows the sample of speed curve for head sea case.

The speed curves plotting are based on mathematical relationship between power output, RPM and speed. Figure 10 shows sample of RPM vs. speed curve and Figure 11 shows sample of power vs. RPM curve. Both samples are for the head sea case. As for RPM vs. speed plot, the trend is found to be linear while power vs. RPM is a power curve. Combination of both produced the speed curve. Initial analysis for both plots was only considering the three boundaries i.e. lower, upper and median. This is sufficed as the speed curve is also represents by RPM value.

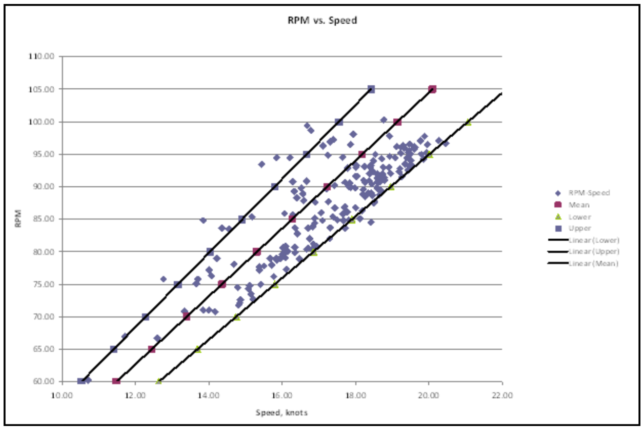


Figure 10 RPM vs. speed (head sea)

Figure 12 shows the different set of speed curves in head sea; indicate by polynomial or power curve. Each set is a RPM-based value. For instance, at 100 RPM mark, corresponding power and speed values of lower, median or upper boundaries are plotted. For all RPM cases, each plot is connected based on this boundary. The curve between these three references boundaries is then plotted; an approximation at mean value is considered sufficient in this case. In total, nine (9) speed curves are plotted for each case.

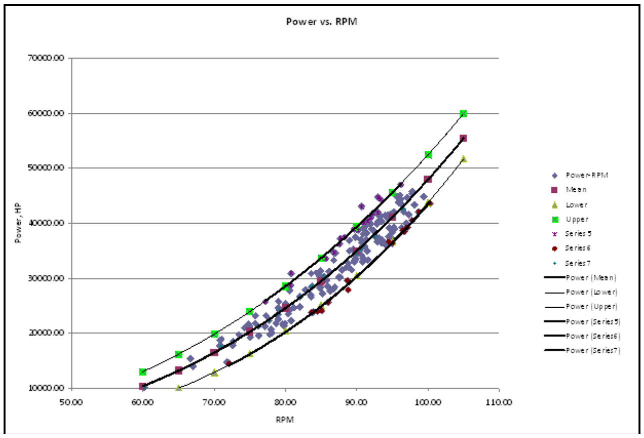


Figure 11 Power vs. RPM (Head Sea)

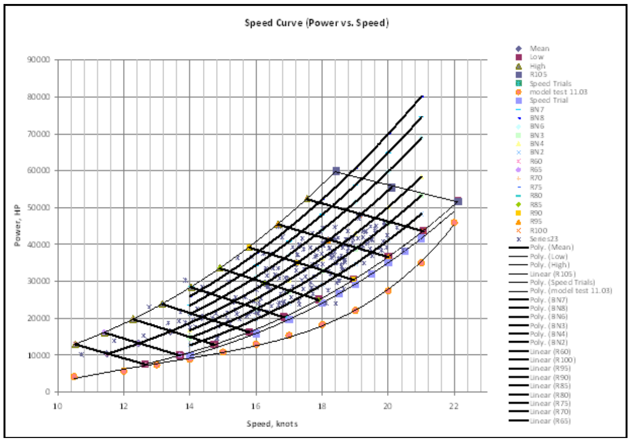


Figure 12 Speed curve or power vs. speed (Head Sea)

Theoretically, each speed curve shall represent the summation of resistance factors that acting on ship. The calculation of the ship speed in seaway is based on Newton's law that dictates shall the sum of all forces acting on ship is equals zero, the acceleration is zero and therefore the derived speed is constant.

Let's consider for the lower curve, this shall represent the least resistance or good weather case. Details analysis shows that lower curve or also the first curve from total 9 curves is the speed curve at Beaufort 2 at Beaufort scale (hereafter Beaufort scale is abbreviate as "BF").

Prior to this conclusion, calm water resistance curve at similar draught extracted from Figure 9 and speed trial result curve are plotted against those nine speed curves. The speed trial curve, in details analysis, is confirmed as the speeds curve that corresponding to the calm water resistance curve. This analysis is also taking into consideration of propeller efficiency and other loses; by reverse calculation of speed calculation as introduced by Journee (1976) and Journee and Meijers (1980). They state that the thrust which can be gained by the propeller must be equal to the sum of still water resistance and added resistances. With this equilibrium the speed through the water can be calculated. Figure 13 shows the speed calculation scheme based on above explanations.

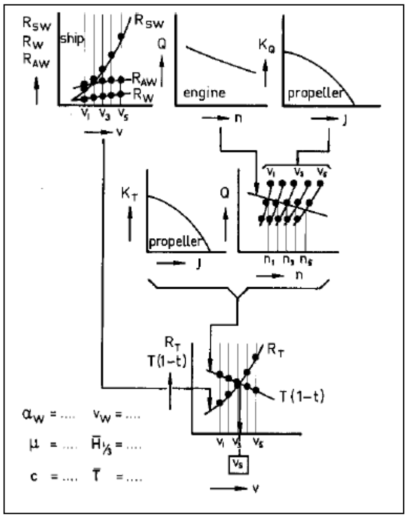


Figure 13 Scheme of speed calculation (Journee, 2001)

Accordingly, based on the speed trial curve, the lower curve on speed curve is determined as a BF2 case or 0.25 m wave. The determination process is done by using the speed loss ratio between those two curves i.e. speed trial curve and lower curve. Similarly, another eight curves are then determined as to be represented by respective Beaufort scale. In summary, it is concluded that median curve (5^{th} curve) is represent BF8 and the 7^{th} curve is represent BF9. Other curves (2^{nd}, 3^{rd}, 4^{th} and 6^{th}) are determined as a relative BF or wave height corresponding to those BF2, BF8 and BF9.

As for the 8^{th} curve and upper curve (9^{th} curve) cases, detail analysis confirmed that these curves are represent BF9 of after 2.5 years and 5 years fouling effects respectively (Details on fouling is in Sub-topic 3.7). In other word, every step of curve is also represent approximately 2.5 years of fouling effect. For instance, 2^{nd} curve is a BF2 after 2.5 years of fouling. Table 3 shows the summary of speed curves and corresponding BF. It is however, more consideration shall be taken of for the application to any other ship as this “rule” may only true for Tenaga class case. Fouling trend effects may differ on case by case basis.

Table 3 Speed curves and corresponding beaufort scale

Curve	Case
Speed Trial	Calm Water Resistance
1st curve (lower)	BF2 or 0.25m SWH
2nd	BF2 + 2.5 years
3rd	Mean SWH between 0.25m and 6.5m
4th	SWH between 0.25m and 6.5m
5th curve (median)	BF8 or 6.5m SWH
6th	BF8.5
7th curve	BF9 or 8.5m SWH
8th curve	BF9 + 2.5 years
9th curve (upper)	BF9 + 5 years

Similar kind of approach is also done for the other four heading cases i.e. beam, following, bow quartering and stern quartering seas. Calm water resistance or corresponding speed trial curve is consider same with the head sea case; since this is “calm water” or “no wave and wind” case. Therefore, the determination of corresponding BF is also following the similar conclusion as per Table 2.

From the speed curve, effect of weather and/or fouling effects to the ship performance can be seen clearly. Similarly, attained speed of respective RPM and/or power output at any BF can be calculated. This is indeed provides a simple but powerful descriptions on the performance behaviour of the ship in any weather conditions.

Various calculations are carried out to validate the performance curves, from various points. Table 4 provides the summary of the validation calculation.

3.6 Service Margins

The performance evaluation of ship in a seaway is primarily based on calm water resistance as a first estimation of the power required. An allowance is added to this value to include anticipated weather effects by inclusion of sea margin, independently from actual behaviour of the designed ship in a seaway. Required sea margin value is usually stated at the design stage by the ship owner or ship designer and often between 15–30% of the engine output of calm water curve, based on tradition or experience from similar ships sailing on the same route. Powering margin, according to ITTC (2005), can be defined as the margin which should be added to the estimation of the speed-power relationship for a newly built ship in ideal weather conditions to allow for the operation of the ship in realistic conditions.

Figure 14 shows the sea margin calculation for Tenaga class based on NCR load. Comparison is then made against the BF5 of head case. Consider this is a newly design ship and 21% of sea margin is imposed at NCR power, the attained speed is about 20 knots. By comparison this is approximately equivalent to the BF5 of head case.

According to the technical specification of Tenaga class, the ship was guaranteed to achieve at least 19.5 knots at similar conditions. The 0.5 knots different is considered as an additional margin included by designers. This is somehow may be also consider as a hidden effect of propeller margin; a new or polished propeller performs about 2-7% better than it designs value.

Table 4 Summary on validation calculations

Case	Validation Approach	Reference/Model
Speed Trial Curve	1. Calm water resistance. 2. Reverse calculation of speed-thrust equilibrium.	1a. Actual model result. 1b. Prediction Methods (Holtrop and Mennen, 1982). 2a. Journee (1976). 2b. Journee and Meijers (1980).
Lower Case (1st curve)	Speed trial curve comparison.	Sea trial results.
Lower Case (1st curve)	Speed loss calculation comparison.	Townsin and Kwon (1982). Kwon (2008).
2nd - 9th curves	Speed loss calculation comparison.	Townsin and Kwon (1982). Kwon (2008).
2.5Y curve	Fouling effect analysis.	Figure 14.
5Y curve	Fouling effect analysis.	Figure 14.
All curves (1st - 9th)	Ship routeing simulation i.e. voyage duration and FOC.	Actual voyage data.
5th curve (Correspond to BF 8)	Transfer function of wave added resistance	Test result from: 1. Hermans (2005) 2. Blok (1993)
All data input	SWH or Wind Speed comparison.	NMRI database.
All curves	Speed loss corresponds to added resistance.	Townsin and Kwon (1982). Kwon (2008).
All curves	Speed loss at constant power.	Townsin *et al.* (1993).
All curves	Power increase at constant speed.	Townsin *et al.* (1993).
All curves	Added resistance by reverse calculation of speed-thrust equilibrium – *Recommended for future work.*	Established added resistance prediction methods

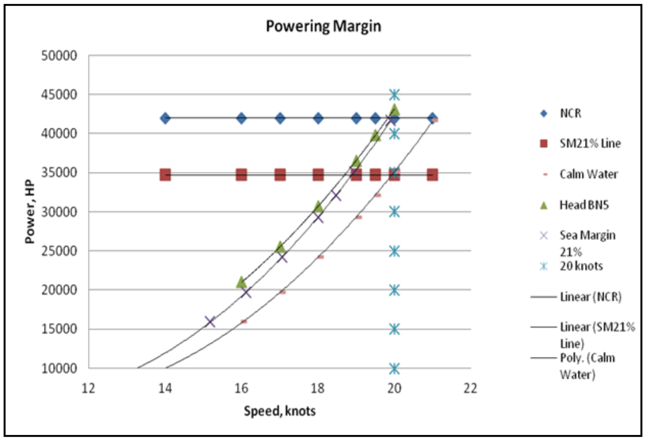


Figure 14 Powering margin of NCR power

3.7 Hull and Propeller Fouling

Figure 15 shows the average effect of hull and propeller fouling over time. From the noon reports, the total daily fuel consumption (FOC) is a function of voyage distance and duration. In simple explanation, fuel consumption increased if the voyage duration and distance per day increased. It is sufficient to perform such simplification, in this case, as at the same time; duration and distance are actually a function of speed, rpm and engine output.

It shall be noted that Figure 15 represent analyses from one ship of Tenaga class at laden draught. Strictly speaking, between same classes of ships, the plot may show different trends.

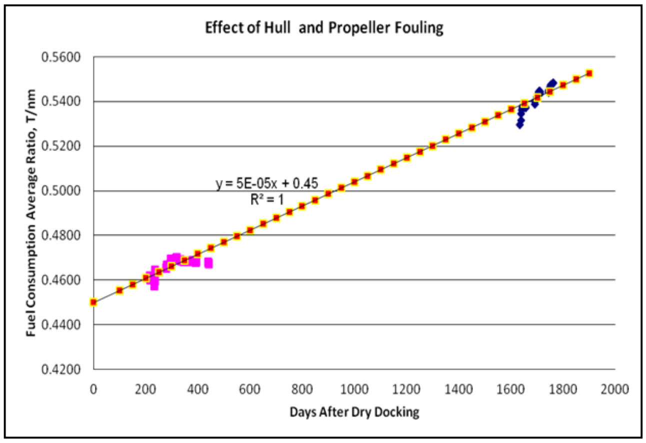


Figure 15 Effect of hull and propeller fouled over time

In Figure 15, average daily FOC per distance is plotted against duration. In this particular case, the time is referring to the number of days after delivery or dry-docking. Though the total daily FOC is varies, but averaging value over time shows otherwise. Ergodic characteristic is observed in the averaging trend and it is deduce as an effect of hull and propeller fouling. In general, other influence factors such as weather or attained speed show randomness over time but fouling effect shows close agreement with increment by near-linear trend over time.

For further note, it shall be assumed that, whether or not hull and propeller cleaning is performed at dry-docking period, the fouling will deteriorate over time. The only set back is that the deteriorate rate is rather unique; fouling rate is different across the fleet due to hull roughness, applied anti-fouling paint, operation practices and etc. Thus, to know such rate at early stage is a matter of prediction or assumption.

The simplified formula is strictly based on the 24 hours or per day rule. For instance, as shown in Figure 15, the FOC/nm ratio on the 0 day after dry-docking is 0.45 MT/nm. Let's assume, in any given engine output, rpm or attained speed, the total distance achieved in that particular 24 hours is 100 nm. Thus, the FOC for that particular day is estimated at 45 tonnes or for the total 2000 nm voyage, the total FOC is 900 tonnes. Accordingly, the same calculation can be applied for any days from dry-docking, follows the near-linear trend or its empirical equation.

The plot shows average FOC ratio is increased linearly over period of time. In 5 years or 1825 days after dry-docking, the FOC/nm ratio is increased by approximately 0.1 tonnes per nm. In simple manner, increase in fuel consumption after 5 years is estimated at 10 tonnes for every 100 nm distance travelled. For complete 2000 nm laden voyage, increase of 200 tonnes is estimated. This is indeed a substantial increment, thus, the effect of hull and propeller fouling to the FOC is great. By increasing docking or hull and propeller cleaning frequency, the average loss could be substantially reduced.

Further details calculation is made based on empirical formula of fouling effect trend, taking into consideration the effect of fouling to the additional power requirement and speed loss for the after 5 years case, as per Figure 16. A typical result in speed reductions is about 5% at constant engine power output and a power increase is about 20% at 19 knots case. The calculation is made following the fine weather performance curve. The percentage in speed reductions or power increase varies in different set of weather conditions.

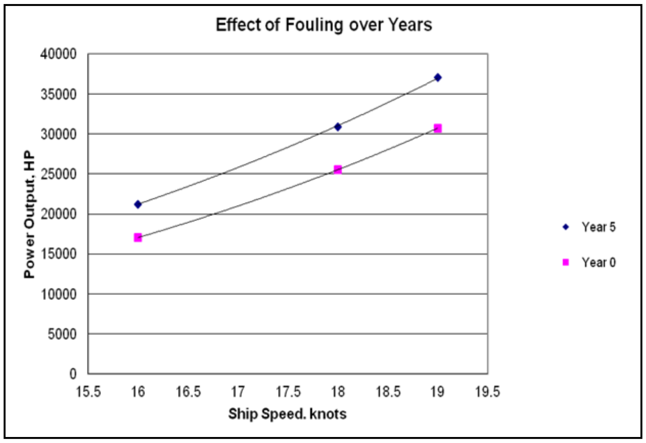


Figure 16 Effect of Fouling over Years

3.8 Effect of Ocean Current

The ocean current plays an obvious role in determining the ship's ground speed according to Chen (1978). The ship's speed and heading is that required to overcome the effect of current (Calvert, 1990). Both Chen (1978) and Calvert (1990) have concluded that the actual ground speed and heading becomes a vectoral summation.

In the case of current movement coming from head direction or 180° heading, the ship is moving against it or speed through water (STW) is smaller than speed over ground (SOG). That is to say the ship movement through water is more than her movement over ground. In an opposite direction case, the current will increased the SOG of the ship. Therefore additional speed is gained. In simple vector summation:

$$SOG = STW \pm Current \qquad (1)$$

Where positive (+) is for following direction current and negative (-) is for heading direction current. For the case of current from beam or quartering direction, there is a need for heading correction and speed adjustment.

Figure 17 shows the percentage of current occurrence in Bintulu-Far East route. It is obvious that about 60% of the occurrences are negative current cases, for both laden and ballast voyages. Comparison between laden and ballast voyage proved that occurrence of currents are almost balance. The occurrence of the current could be related with the Kuroshio Current. The Kuroshio is a north-flowing ocean current on the west side of the North Pacific Ocean and known for its high velocity.

Post mortem on voyage records are carried out to detail out the current effect to Tenaga class, as per Figure 18. No details on current speed, ship heading or drift angle, but the resultant effect can be estimated from Equation (1). In this case, the current effect represents the average speed loss or gain. It is found that the average current effect, either positive or negative, is varying in each weather zone. The highest value is at -0.5 knots and +0.26 knots. Comparison between loading case, average value is -0.18 knots for ballast case and +0.074 knots for laden case. Though in overall summation, the current effect proved to be almost even or zero current effect, this may pose deceiving fact. The best representation shall be on the case by case. Well routed ship will gain positive boost that equivalent to time and money benefit from the favourable current or else otherwise.

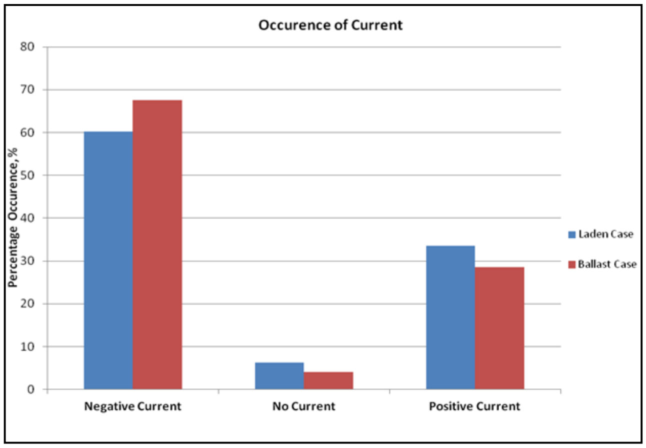
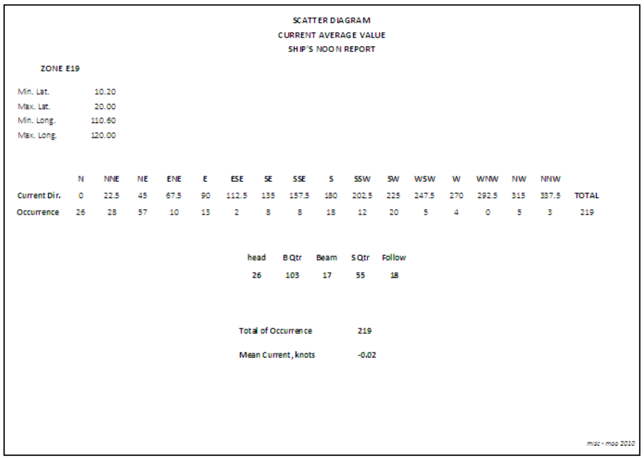


Figure 17 Occurrence of current in Bintulu-far east route



SCATTER DIAGRAM
CURRENT AVERAGE VALUE
SHIP'S NOON REPORT

ZONE E19

Min. Lat.	10.20
Max. Lat.	20.00
Min. Long.	110.60
Max. Long.	120.00

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	
Current Dir.	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	TOTAL
Occurrence	26	28	57	10	13	2	8	8	18	12	20	5	4	0	5	3	219

head	B Qtr	Beam	S Qtr	Follow
26	103	17	55	18

Total of Occurrence	219
Mean Current, knots	-0.02

misc - mao 2010

Figure 18 Sample of ocean current data analysis

Let's consider the worst case scenario; as if the current effect for a total 1000 nm ground distance voyage is constantly at -0.5 knots. Due to this negative current, at no current corresponding ship speed of 18 knots, the ship is effectively forced to travel 28 nm and 1.59 hrs extra. The effect is even worse shall we consider the extra fuel consumption needed and corresponding green house emissions during the voyage.

3.9 Fuel Consumption

Tenaga class was fitted with steam turbine as main propulsion, a standard installation for any LNGC before been replaced with more advance DFDE or TFDE engines. The main reason behind selection of steam turbine is to make full use of the natural boil-off gas generated from the cargo tanks during voyage. For the discussion from here on, we shall considered steam turbine as an engine and fuel represents the boil-off gas and/or fuel oil.

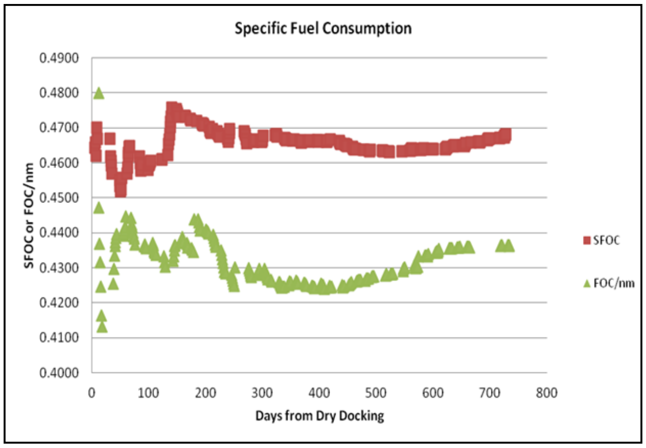


Figure 19 Average specific fuel oil consumption (SFOC)

Figure 19 shows the trend of average SFOC and daily FOC/nm ratio against days from dry-docking. Again, the plotting is to show the ergodic trend that resulted from time effect. The voyage practice may differ from time to time, this is considered as random and average value therefore is the best indicator.

In this particular graph plot, early trend indicate a scattered average value for both SFOC and FOC/nm ratio. Over time, the values start to show the true behaviour and this may be seen from the 400 days onwards. Again, the trend increment over time is related to the hull and propeller fouling effect. The increase in fuel consumption may also result of engine efficiency degradation over time.

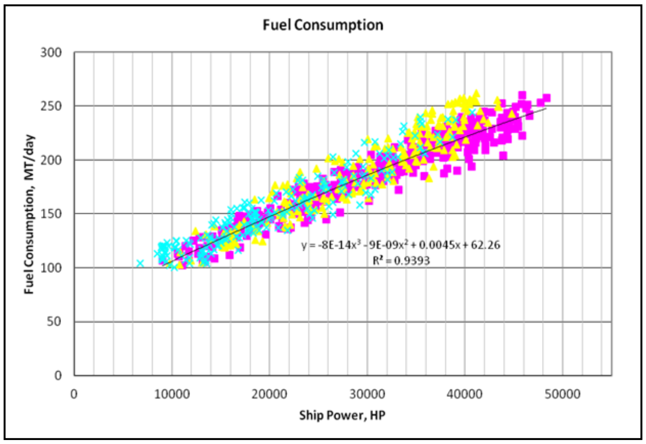


Figure 20 Daily fuel oil consumption curve

Similar kind of effect can be seen in Figure 20. This figure shows the daily fuel consumption against the engine output. Over time, the daily FOC values are scattered within consistent deviation over average FOC empirical line. For approximation purpose, this empirical formula may be used to estimate daily FOC value. The formulation consider that in any given weather conditions or loading pattern, the average FOC is a function of engine output. This is indeed easy to understand and to use. Further ship routeing analysis has proved that as for 5 days voyage, estimated FOC is within 5% of actual FOC and more accurate results are obtained for the "near-constant case". It is shall be accepted that the daily FOC is resulted from combination effects of various weather conditions. Near-constant case represents a more consistent weather condition or constant effect from weather for that particular day.

As for a new engine case, the FOC is normally estimated by using designed or actual SFOC curve. The SFOC is the best indicator of the engine performance upon that time; it is by standard to be guaranteed within 5% above designed SFOC. Thus, engine from similar model may generate different SFOC.

3.10 Seakeeping and Ship Motion

No specific calculation attributes to the seakeeping and ship motion values are made. This omission is decided on the basis that there is no physical ways of validate the calculation or prediction, as far as actual data is concerned. No onboard record on ship motions are recorded since there is no motion sensor installed on the ships. This is in fact a standard for any other LNG carriers as no rules and regulations required such installations, unless it is from the owner's specific request.

Furthermore, it is well accepted that the actual voyage had successfully taken place; this generate conclusion that the ships were operated within the seakeeping and ship motion limits. Or else, voluntary speed reduction decision was taken to ensure the ship is always in the acceptable region for both safety and operability terms.

In this regard, however, it is fully admitted the importance of seakeeping and ship motion in ship operations. For instance, in carrying out ship routeing simulation or prediction, it is vital important to precisely predict the ship's motions and the probabilities of occurrence of accompanying phenomena such as green water, slamming, propeller racing, accelerations etc in actual sea conditions. This prediction is part of system and model constraints in ship routeing algorithm.

3.11 Loading Conditions

The effects of loading pattern can be represents by physical conditions of ship i.e. draught and trim and motion in response. As has been discussed earlier, the laden case is considered to be consistent and not for ballast case. Figure 21 shows the power vs. RPM plot for ballast condition in head sea and least resistance case in represented by the curve. From the graph, a few more data are plots ahead of the curve. This is a result of draught and/or trim different in ballast voyage e.g. heavy ballast and light ballast cases.

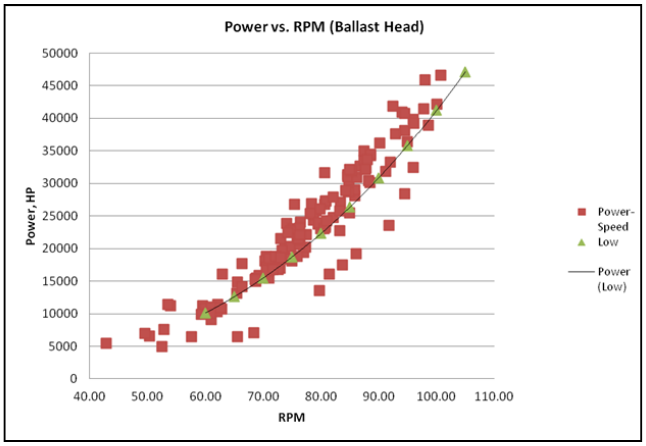


Figure 21 Power vs. RPM for ballast head case

There are ways to estimate the effects of draught and trim change. The simplest method is by using the Admiralty coefficient, a ratio between power and displacement as per Equation (2).

$$BHP_2 = BHP_1 \left(\frac{\Delta_2^{2/3}}{\Delta_1^{2/3}} \right) \tag{2}$$

3.12 Significance and Benefits of Study

Service performance is a true representation of ship performance in actual operation conditions. Close representation of ship performance in actual seas is prerequisite to further benefits that can be drawn. The benefits or significance are summarised in Table 5 as follows:

Table 5 Benefits and significance of study

No.	Analysis/Model	Benefit/Significance
1.	Weather Observation	Weather Scatter diagram analysis
2.	Route Tracking	Strategic route analysis
3.	Service Performance	1. Ship routeing (pre-voyage) 2. Post voyage management 3. Future design for service 4. Ship performance comparison 5. Charter party agreement 6. Voyage simulation 7. Added resistance study
4.	Fouling Effect Analysis	1. Ship routeing 2. Selection of A/F paints
5.	Current Effect Analysis	Ship routeing
6.	Seakeeping Analysis (*Recommended for Future Study*)	Improve voyage integrity (safety, habitability, operability)

4.0 CONCLUDING REMARKS

Service performance of LNG carriers in actual seas derived from post-mortem on collection of years of voyage's noon reports is briefly discussed in this paper. The comprehensive discussion is summarised and organized into eleven (11) sub-topics. Each topic is briefly elaborated in term of, but not limited to, technical background, analysis results, significance of results and result discussions. It is shall be noted that though not all formulae or empirical equations are given in this paper, all the results or figures are extracted from, if not rigorous, a thorough analysis based on theoretical work, empirical or approximation formulae, graph analysis, heuristic and cognitive approach, and last but not least, validation against works of others and actual full-scale results. By having mentioned that, further reference can be made to the work of all mentioned authors and works in this paper, as provided in the reference list.

It is admitted that some aspects of ship performance are intentionally left out from this paper i.e. seakeeping analysis and results as a comparison with added resistance prediction method. These are however recommended for the future investigations and discussions.

Nevertheless, this paper has provided insights into service performance of LNG carriers in actual seas. The economic, design and operation benefits gained from this analysis, as summarised in Table 5, has further indicate the importance and the need for such analysis for newly design and in-service ships.

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