A holistic approach to Reliability and Safety on the operation of a main propulsion engine subjected to a harsh working environment.

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Abstract – *The main propulsion engine of a vessel has to operate under harsh environmental conditions that includes very rough weather, concurrent failure of one or more units of the engine and failure of one or more subsystems of the main engine. Such failures at high seas could lead to disastrous consequences, which could include damage to ship's machinery, injury and fatality of shipboard personnel and pollution of the sea. Reliability and Safety of the main propulsion engine needs to be looked at holistically when the main engine operates under harsh environmental condition. Mathematical modelling for computing reliability of the main propulsion engine, combined with a relevant safety check list for the engine room, based on expert elicitation could be a good solution for an unremarkable voyage of the vessel under a harsh scenario. This paper intends to look at the harsh scenario for a bulk carrier propelled by a large main propulsion engine and arrive at a plan for a safe and reliable voyage of the vessel*

Keywords: Holistic, reliability, safety, harsh, bulk carrier, expert elicitation.

1. INTRODUCTION

Reliability and Safety are two vital factors when it comes to operation of a main engine propelling large capacity modern bulk carriers at high seas. A main propulsion engine is associated with a number of sub-systems for its operation. The sub-systems are the main engine lube oil system, the main engine fuel oil system, the main engine cooling water system and the scavenge system. The reliability of the main propulsion engine is dependent on the reliability of its sub systems, (EPSMA, 2005; Mollenhauer & Tschöke, 2010).Various methods could be adopted to determine the reliability of the subsystems depending upon the failure rate exhibited by the system components, (Dhillon, 2002). A combination of constant failure rate and time dependent failure rate modelling was used to determine the reliability of the subsystems,(Xie & Lai, 1996). Thus the reliability of the main propulsion engine is determined. A mathematical model can determine the reliability of the main engine propelling a bulk carrier under normal sea condition. However, when the bulk carrier is subjected to harsh environmental conditions, then we need to consider additional factors to ensure safety of the vessel. The harsh environmental condition mainly comprises of bad weather, when the main engine could encounter failure of one or more cylinders, thereby necessitating operation of the engine at a reduced load in order to get the vessel to a safe heaven. There is also the likelihood of failure of the ship's power generation machinery failure under harsh working environment, which would be a matter of very high concern related to the safe operation of the vessel. Also when it comes to running of a bulk carrier, it is vital that we consider both the ballast and the loaded condition, when the operating conditions are different,(Krüger, Steinbach, Kaufmann, & John, 2010).This paper aims to look into all the above factors and ensure safe operation of the bulk carrier under harsh working environment.

2.RELIABILITY

2.1. Reliability of the main engine safe and remarkable voyage of a bulk carrier

R_{MEN} : Reliability of the min engine at normal power
P_{nor}: Main Engine normal power
S_v : Safe voyage
S_{chk}: Safety check list
P_{red}: Main Engine reduced power
R_{MEH} : Reliability of the main engine in harsh environment
R_v : Remarkable voyage

A bulk carrier is a vessel which carries cargo in bulk, the cargo could be grain, coal, industrial salt and iron ore, to name a few. The cargo carrying capacity of a bulk carrier may vary between 3000 dwt to 400,000 dwt. Generally, these bulk carriers are propelled by large two stroke marine diesel engines, referred to as main engine. The reliability of the main propulsion engine R_{MEN} will be

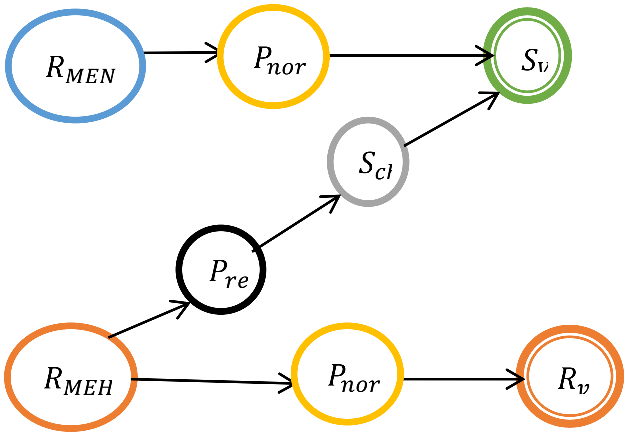


Figure 1: Events comparing a safe voyage and a remarkable voyage for a bulk carrier

dependent on the reliability of a number of its sub systems, which includes the lubricating oil system, fuel oil system, scavenge system and cooling water system. The main engine will be generating its normal power P_{nor}, when the bulk carrier is operating in gentle environmental condition. Markov and Weibull modelling (Richard E Brown; Srinivasa Rao & Naikan, 2016),(Duffey & Van Dorp, 1999) techniques have been used to determine the reliability of various main engine sub systems and having done so, the reliability of the main engine could be determined from the reliability block diagram (RBD) as shown below.

2.2. Reliability block diagram (RBD) for main engine and evaluating reliability of main engine

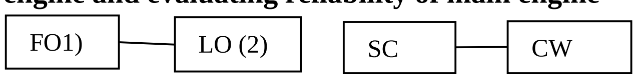


Figure 2: Reliability block diagram for main engine

$$R_{MEN} = \prod R_{i_{i=1,2,3,4}} = \prod R_{i_{i=LO,FO,SC,CW}}$$

i= 1 is the fuel oil system (Marrkov modelling)

i =2 is the lubricating oil system (Markov modelling)

i= 3 is the scavenge air system (Weibull modelling)

i = 4 the cooling water system (Markov modelling)

A safe uneventful voyage of the bulk carrier is denoted as S_v. Hence the safe voyage of the bulk carrier

$$S_v = f(R_{MEN}, P_{nor})$$

On the contrary when the bulk carrier is subjected to a harsh environment at sea this could be an entirely different scenario. The safety features bulk carriers have been highlighted by the IMO (International Maritime Organization,www.imo.org, 01.05.2017), in their work on Bulk Carrier Safety. This includes safe loading, discharging and carriage of bulk cargo. It also features the various safety measures employed in the safe design of bulk carriers. Also based on extensive research, IMO has prescribed additional measures for bulk carrier safety in SOLAS (safety of life at sea). Accordingly, when subjected to harsh working environment, the bulk carrier need to account for a number of factors, to ensure a safe voyage. Failing to account for the necessary factors, the end result could be a remarkable voyage. The main factors which could add to an eventful cago would include , R_{MEH}, the reliability of the main engine under harsh environmental condition, P_{nor} the normal power of the main engine, which is the same as that when the main engine is operating in a gentle environmental condition.

To ensure a safe voyage for the bulk carrier under harsh working environment, it is absolutely necessary for the main engine propelling the bulk carrier be run at a reduced power P_{red} to ensure safety of the hull, machinery and the ship's crew,(Khan & Haddara, 2003)Also it is necessary to develop a safety check list S_{chk} based on expert elicitation to eliminate the possibility of an eventful or remarkable voyage R_v.

$$R_v = f(R_{MEH}, P_{nor}).$$

A safe voyage in a harsh working environment could be represented as shown below

$$S_v = f(R_{MEH}, P_{red,} S_{chk}).$$

$$R_{MEN} = \prod R_{i_{i=1,2,3,4}} = \prod R_{i_{i=LO,SC,CW}}$$

The power developed by the main engine under normal operation will be proportional to the Reliability under normal operation. This is mathematically stated below

$$P_{nor} \propto R_{MEN} \therefore P_{nor} \propto \prod R_{i_{i=LO,SC,CW}} \quad \text{or}$$

$$P_{nor} \propto R_{LO} * R_{FO} * R_{sc} * R_{cw}$$

When subjected to harsh working environment, the main engine should be run at a reduced load, to keep the load variation to a minimum, else it could lead to major damage to the engine components and components of the sub systems. At reduced load the power developed will be reduced P_{red} and we assume that this will be proportional to the reliability of the main engine at the reduced reliability for a harsh environment and mathematically stated as below

$$P_{red} \propto R_{MEH}.$$

Table 1 Reliability compensating factor k_i

Main Engine Subsystem	System components	Type of failure	Reliability compensating factor
Main Engine Lube oil system	Lube oil filters	Partial and total clogging of filters	k_{lf}
	Lube oil pumps	Tripping of pumps due to overload	k_{lp}
Main Engine Fuel oil system	Fuel oil tank quick closing valve	Abrupt closing of valve	k_{fq}
	Fuel oil filters	Partial and total clogging of filters	k_{ff}
	Fuel oil pumps	tripping of pumps due to overload	k_{fp}
	Fuel oil temperature control vale	Malfunction of control valve	k_{ft}
Main engine Scavenge System	Turbochargers	Surging	k_{sc}
Main Engine Cooling water system	pumps	tripping of pumps due to overload	k_{cwp}
	Cooling water temperature control valve	Malfunction of control valve	k_{cwt}

2.3 Load reduction factor k and reliability compensation factor k_i

We now define a reliability compensating factor for each of the component of the subsystem, to evaluate R_{MEH}

We shall now define a load reduction factor which is the ratio of the normal power to the reduced power of the main engine in a harsh environment $\frac{P_{nor}}{P_{red}}$ =k. We would also like to define a reliability compensating factor k_i, under an assumption that the reliability at the reduced load in a harsh working environment is a function of the load reduction factor k. Since reliability of any the main engine sub system components are a function of its failure rate λ, it is reasonable to assume that the reliability at a reduced load will have a failure rate $\frac{\lambda}{k}$.

$$R_{MEH} = k_{lf}k_{lp}R_{LO} * k_{fq}k_{ff}k_{fp}k_{ft}R_{FO} * k_{lf}k_{lf}R_{sc} * k_{cwp}k_{cwt}R_{cw}$$

$$\frac{P_{red}}{P_{nor}} = \frac{R_{MEH}}{R_{MEN}} = \frac{kP_{nor}}{P_{nor}}$$

$$\frac{k_{lf}k_{lp}R_{LO} * k_{fq}k_{ff}k_{fp}k_{ft}R_{FO} * k_{lf}k_{lf}R_{sc} * k_{cwp}k_{cwt}R_{cw}}{R_{LO} * R_{FO} * R_{sc} * R_{cw}}$$

$$\boldsymbol{k} = \frac{k_{lf}k_{lp}R_{LO} * k_{fq}k_{ff}k_{fp}k_{ft}R_{FO} * k_{lf}k_{sc}R_{sc} * k_{cwp}k_{cwt}R_{cw}}{R_{LO} * R_{FO} * R_{sc} * R_{cw}},$$

which gives us $k = k_{lf}k_{lp} * k_{fq}k_{ff}k_{fp}k_{ft} * k_{sc} * k_{cwp}k_{cwt}$

2.4 Sample calculation of reliability compensator factor k_{lf} for main engine lube oil filter

Table 2: State diagram for lube oil flter

State	Filter 1	Filter 2
1	clean	clean
2	clean	clogged
3	clogged	clogged

Figure 3: Lube oil suction strainers for the main engine lube oil system

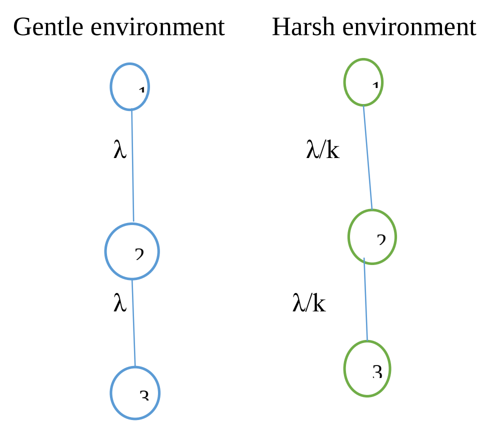


Figure 4: State diagram for lube oil filter

As shown in Table 2, there are 3 states. In this case the two main engine lube oil pump strainers are identical standby units, one of which is on line and the other standby.The reliability of the two identical systems isderived as, $R_f(t) = e^{-\lambda t}\sum_{i=0}^{1}\frac{(\lambda t)^i}{i!}$.

In this case $R_f(t) = e^{-\lambda t}(1+\lambda t)$ and MTTF (Mean time to failure) $= 2/\lambda$

The above equation holds for gentle environmental condition of the main engine lubricating oil sub system. When subjected to harsh woorking environment we make an assumption that the failure rate of the engine component wil be proportional to the reduced power P_{red} on the main engine. The modified reliabiliy for the lue oil filter can be shown to be $R_{fh}(t) = e^{-\frac{\lambda t}{k}}(1+\frac{\lambda t}{k})$,

where k is the reduction load factor, which has to be adjusted in a harsh working environment.

The reliability compensating factor for the lube oil filter may then be determined as follows:

$$k_{lf} = \frac{R_{fh}(t)}{R_f(t)} = \frac{e^{-\frac{\lambda t}{k}}(1+\frac{\lambda t}{k})}{e^{-\lambda t}(1+\lambda t)} = \frac{(1+\frac{\lambda t}{k})}{e^{\frac{1}{k}}(1+\lambda t)}$$

On the same lines the reliability compensating k factors for the other system components could be determined. We would expect the product of all the reliability compensating values to be close to the reduction load factor of the main propulsion engine under harsh working environment.

2.5 Markov modelling for lube oil filter

Table 3: Reliability of lube filters

Reliability of Lube oil filters		
λ = 4.53*10^-6 , t =2000 hrs		
R(lf) at normal load e^(-λt)(1+λt)		
R(lf) at reduced load k	e^(λ/kt)(1+λ/kt)	
k	R(lf)	
1	0.999959	
0.9	0.99995	
0.8	0.999936	
0.7	0.999917	
0.6	0.999887	
0.5	0.999838	
0.4	0.999747	
0.3	0.999553	
0.2	0.999004	
0.1	0.996136	
klf	**0.996176**	

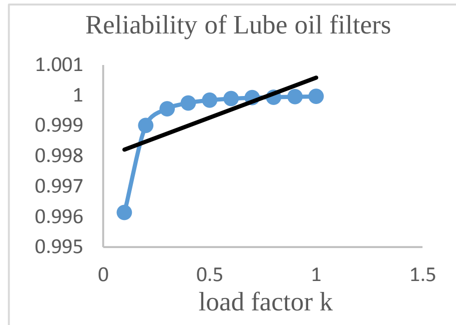


Figure 5 : Reliability vs load factor of lube oil filters

2.6 Weibull modelling for Turbocharger

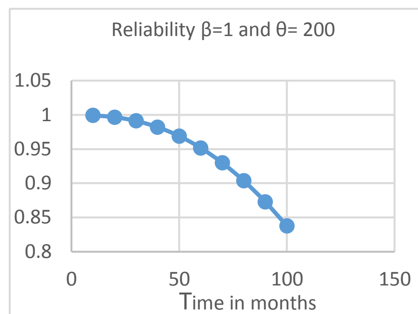


Figure 6 :Reliabiity vs time of Turbocharger

Tabe 4 : Reliability of Turnochargers

t	Shape factor β=3	Char. lie θ	Reliability at β=3	Shape factor β=1	R(t) β=1
10	3	200	0.999875	1	0.951229
20	3	200	0.999000	1	0.904837
30	3	200	0.996630	1	0.860708
40	3	200	0.992031	1	0.818730
50	3	200	0.984496	1	0.778800
60	3	200	0.973361	1	0.740818
70	3	200	0.958031	1	0.704688
80	3	200	0.938005	1	0.67032
90	3	200	0.912903	1	0.637628
100	3	200	0.882496	1	0.606530

3.0 SAFETY ASPECTS

In Table , the reliability compensating factor was calculated as aratio of R(lf) at 0.1 % of normal load to R(lf) at normal load and the value of klf was 0.96176. Similar analsis was done for all other system components. The derivation of the formula for k in2.3 above was based on the assumption that at reduced load we need to compromise on reliability. But calculations from available dta has shown that the sfaety aspect may have a major impact on the vessel operation in a harsh environment.A case study of vessel accidents from Australian Transport Safety Bureau (ATSB) data (ATSB, 2003, 2011, 2012, 2016) were analysed in this study and tabulated as shown in Table 5 below.

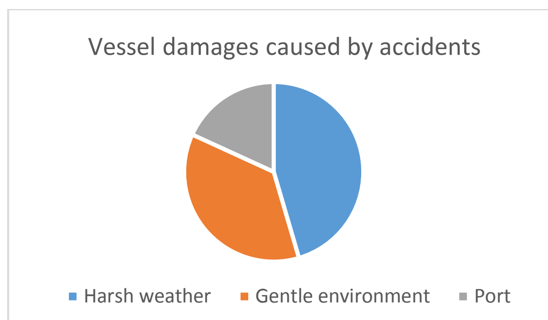
Table 5: Vessel accidentssourced from Australian Transport Safety Bureau (ATSB)

Year	Vessel	Weather	Damage	Reason
2010	1	HW	Loss of cargo	Lack of training to ship's crew in handling cargo lashing
2011	2	GW	Serious burns sustained by crew member	Breathing Air compresso r explosion on deck
2011	3	P	Serious injury to crew member	Damaged catwalk in the machinery space
2010	4	GW	Damage to vessel	Collison between a bulker and another vessel.
2012	5	P	Damage to cargo	Fire on deck
2011	6	HW	Vessel abandoned	Steering failure
2016	7	HW	Minor damage to ship's structure	Mooring damage
2012	8	HW	Drifting of vessel	Black out and engine failure
2012	9	GW	Serious injury to crew members	Explosion of auxiliary machinery
2012	10	GW	Grounding f vessel	Steering failure
2014	11	HW	Vessel touching the wharf	Propeller control system failure

3.1 Safety check list

A safety check list has been developed based on ATSB research and expert elicitation, (Roberts, Pettit, & Marlow, 2013).This will be useful to perform a safe voyage of the vessel under a harsh environment.

Sample check list for harsh environment	
Main engine lube oil system	Lubricating oil system Filters to be cleaned irrespective of PMS hours
Main engine fuel oil system	Check fumctioning of quick closing valve, temperature control valve irrespective of PMS hours
Main engine scavenge system	Clean air inlet filters, replenish oil in the lube ol sump bot on tubine and blower side.
Main engine cooling water system	Check function of temperature control and continuously monitor expannsion tank level
Steering gear system	Standby pump to be running, replenish oil in the sytem tank.
Auxiliary engine	Additional diesel generator to be running and sharing load of the plant.
Engine Room gear	Overhead crane to be lashed & no loose gears.



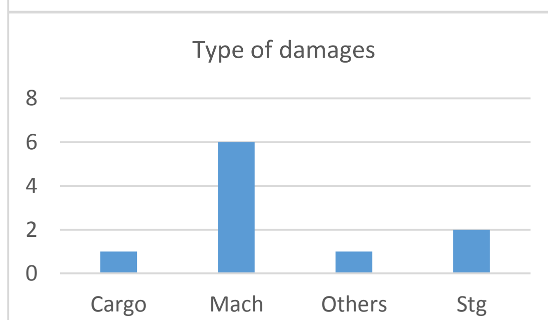


Figure 7 : accident analysis (courtesy Australian Transport Safety Bureau (ATSB)

4. CONCLUSION

In the above paper we have tried to look at the two main aspects, reliability and safety, on the operation of a bulk carrier under harsh working environment. We have compared the relaibility of the main engine ranging from 10% to 100% load, asssuming that the reliability is proportional to the load, and evaluated a reliability compensating factor for the main engine system components, in a harsh working environent.We could conclude that the impact of harsh working environment per se does not impact reliability to a great extent. We need to look at other factors related to safetywhich should include cargo stowage, steering failure and failure of other auxiliary machinery, apart from the main engine failure. We need to take a holistic approach to reliability and saftey, whilst opertaing the main engine in a harsh environment, Thiscalls for further analysis, evaluation and quantification of the safety factors toensure a sae voyage to take place. A safety check list for a safe voyage of the bulk carrier is also presented, based on research and expert elicitation.

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References

ATSB. (2003). Independent investigation into the equipment failure on board the Australian registered bulk cargo carrier Goliath.

ATSB. (2011). *Independent investigation into the loss of cargo from the Panamian registered multi-purpose/general cargo ship Mimasaka off Coffs Harbour, NSW, on 4 October 2010*. (Investigation number: 278-MO-2010-007). Australia: ATSB.

ATSB. (2012). *Collision between the Liberian registered bulk carrier Grand Rodosi and the Australian registered fishing vessel Apollo S in Port Lincoln, SA on 8 October 2010*. (Investigation number: 279-MO-2010-008). Australia: ATSB.

ATSB. (2016). *Breakaway of Spirit of Tasmania II* (324-MO-2016-001). 2016: Australian Transport Safety Bureau.

Dhillon, B. S. (2002). Engineering_Maintenance_a_modern_approach.pdf.

Duffey, M., & Van Dorp, J. (1999). Risk analysis for large engineering projects: modeling cost uncertainty for ship production activities. *Journal of Engineering Valuation and Cost Analysis, 2*(4), 285-301.

EPSMA. (2005). Guidelines to Understanding Reliability Prediction. (24 June 2005), 29.

Khan, F. I., & Haddara, M. M. (2003). Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning. *Journal of Loss Prevention in the Process Industries, 16*(6), 561-573.

Krüger, S., Steinbach, C., Kaufmann, J., & John, F. (2010). *Stability accidents in ballast/laid-up conditions a new phenomenon?* Paper presented at the Proceedings.

Mollenhauer, K., & Tschöke, H. (2010). Handbook of diesel engines. *Handbook of Diesel Engines, Edited by K. Mollenhauer and H. Tschöke. Berlin: Springer, 2010., 1*.

Richard E Brown, G. F., H.L. Willis. (2004),Failure Rate eq inspection, Ieee Transactions on Power Systems, 19(2).

Roberts, S. E., Pettit, S. J., & Marlow, P. B. (2013). Casualties and loss of life in bulk carriers from 1980 to 2010. *Marine Policy, 42*, 223-235. doi: 10.1016/j.marpol.2013.02.011

Srinivasa Rao, M., & Naikan, V. N. A. (2016). A Markov System Dynamics Approach for Repairable Systems Reliability Modeling. *International Journal of Reliability, Quality & Safety Engineering, 23*(1), -1. doi: 10.1142/S0218539316500042

Xie, M., & Lai, C. D. (1996). Reliability analysis using an additive Weibull model with bathtub-shaped failure rate function. *Reliability Engineering & System Safety, 52*(1), 87-93.