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Reliability Assessment of Main Engine Subsystems Considering Turbocharger Failure as a Case Study

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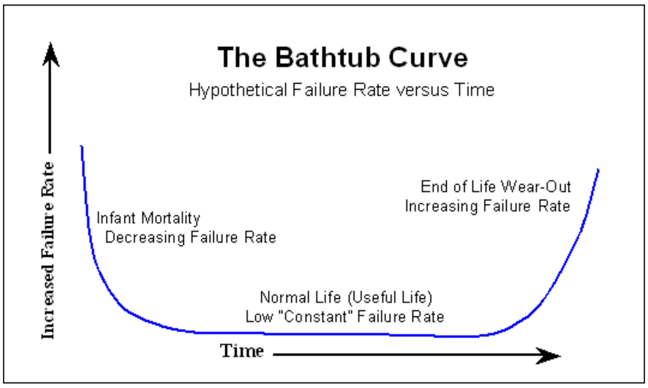
ABSTRACT: Safe operation of a merchant vessel is dependent on the reliability of the vessel's main propulsion engine. Reliability of the main propulsion engine is interdependent on the reliability of several subsystems including lubricating oil system, fuel oil system, cooling water system and scavenge air system. Turbochargers form part of the scavenge sub system and play a vital role in the operation of the main engine. Failure of turbochargers can lead to disastrous consequences and immobilisation of the main engine. Hence due consideration need to be given to the reliability assessment of the scavenge system while assessing the reliability of the main engine. This paper presents integration of Markov model (for constant failure components) and Weibull failure model (for wearing out components) to estimate the reliability of the main propulsion engine. This integrated model will provide more realistic and practical analysis. It will serve as a useful tool to estimate the reliability of the vessel's main propulsion engine and make efficient and effective maintenance decisions. A case study of turbocharger failure and its impact on the main engine is also discussed.

1 INTRODUCTION

The demand for large capacity vessels in commercial shipping has increased over the last decade. These large vessels are propelled by powerful marine diesel engines, It is imperitive that the main engine should have high reliability for safe opeartion of the vessel. The reliability of a vessel's main propulsion engine is dependent on a number of essential sub systems, including fuel oil system, lubricating oil system, cooling water system and scavenge air system. Each of this subsystem has its own individual system components, the reliability of them would dictate the reliability of the corresponding subsystem, (EPSMA 2005; Mollenhauer & Tschöke 2010). Turbochargers form a very important part of the scavenge system and it is essential that the turbochargers have high reliability to ensure reliability of the main engine, (Takashi 194). Failure of turbochragers could lead to disastrous consequences and imobilisation of the main engine. To determine the reliability of the various system components one need to look at the failure pattern depicted by these components. Previous studies have shown that most of the system components in commercial vessels, propelled by large two-stroke engine will fall in the second and third phase of the bath tub curve (shown in Fig 1), which is a constant failure rate followed by an increasing failure rate, (Hashemian & Bean 2011). The reliability of various components of other systems such as gear pumps in a fuel oil system or filters in a lubricating oil system, exhibits constant failure rate (random failure) independent of their history of operation, therefore they could be analysed using Markov modelling. Other major components such as turbochargers exhibits time dependent failure rate.



Phase 1 Infant Mortality, decreasing failure rate (Weibull Analysis)
Phase 2 Useful life, constant failure rate (Markov analysis)
Phase 3 Wear out, increasing (time dependent Weibull analysis)
Figure 1. Bath tub curve for failure rate

The wearing out failure rate can be analysed using Weibull analysis. This paper presents integration of Markov model (for constant failure components) and Weibull failure model (for wearing out components) to estimate the reliability of the main propulsion engine. This integrated model will provide more realistic and practical analysis. It will serve as a useful tool to estimate the reliability and make efficient and effective maintenance decisions. Reliability of Fuel Oil system

Fig.2 below shows a reliability block diagram (RBD) for a main engine fuel oil sysytem. QC represents the Quick Closing valve, FS represents the Fuel Supply pumps, FL is the Discharge filters, FM is the Flowmeter, BT is the Buffer tank, BP represents the Booster pumps, HT represents the steam heater and VIS the Viscotherm. The next step is the analysis of evaluating the reliability of the main engine fuel oil sysytem, by using Markov analysis (Gowid, Dixon & Ghani 2014).

The following points are taken into consideration.

1. Each block represents the maximum number of components in order to simplify the diqgram.
2. The function of each block is easily identified
3. Blocks are mutually independent in that failure of one should not affect the probability of failure of another, (Anantharaman 2013; Xu 2008), (Bhattacharjya & Deleris 2012).

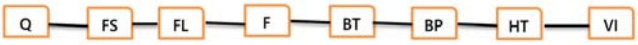


Figure 2. RBD for Main Engine Fuel Oil System

1.1 *Reliability of the Quick Closing Valve*

The quick closing valve is the main tank outlet valve, which can be operated remotely in case of an emergency. If we assume a constant failure rate λ,(PCAG 2012), then the reliability of this component may be expressed as

$$R_{QC}(t) = e^{-\lambda t},$$

where the mean time to failure $\mathrm{MTTF} = 1/\ \lambda$.

1.2 *Reliability of the Fuel Oil Supply pump FS*

The fuel oil supply pumps FS are of the gear type and identical in design and construction. The state diagram for the pumps is shown in figure 4 The reliability function is an exponential function of time t and the failure rate λ expressed as number of failures per running hours, (Bhattacharjya & Deleris 2012).

Table 1. State of Fuel oil supply pump

State	Pump 1	Pump 2
1	Operating	Standby
2	Failed	Operating
3	Failed	Failed

From Table 1 it is clear that there are 3 states. In this case the two fuel oil supply pumps are identical units, Liberacki), one of which is on line and the other standby.The reliability of the two identical systems is derived as,

$$R_s(t) = e^{-\lambda t} \sum_{i=0}^{1} \frac{(\lambda t)^i}{i!}$$

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

Markov analysis is used to compute the reliability of the other componennts in the fuel oil system. The reliability of main engine fuel oil system will be given by

$$R_{F.O.}(t) = R_{QC}(t) R_{FS}(t) R_{FL}(t) R_{FM}(t) R_{BT}(t) \\ R_{BP}(t) R_{HT}(t) R_{VIS}(t) \quad (1)$$

2 RELIABILITY OF LUBRICATING OIL SYSTEM

The next step in the analysis of evaluating the reliability of the main engine lubricating oil sysytem is shown below:

The following five (5) cases s are analysed:

1. Failure of suction strainer S
2. Failre of pumps P
3. Failure of discahrge filter F
4. Failure of Temperature Control Valve TCV
5. Failure of cooler CLR

Each block represents the maximum number of components in order to simplify the diqgram.The function of each block is easily identified. Blocks are mutually independent in that failure of one should not affect the probability of failure of another.(Anantharaman 2013; Xu 2008).

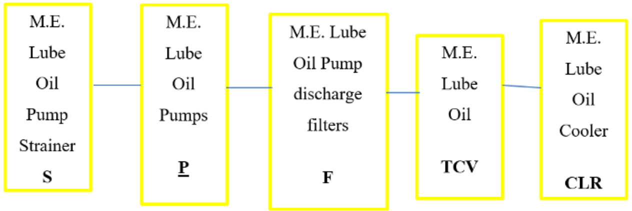


Figure 3. Detailed RBD for M.E. Lube Oil system, with all system components

2.1 *State diagram for the Main Engine Lube Oil Strainer S*

The first component suction strainer S is a basket type strainer, located before the lubricating oil pumps, (Khonsari & Booser 2008).This is a duplex type of filter with a changeover cock for isolation of filters. One of the filters is in use, the second one being a standby. Clogging of the strainer can result in pump's inability to draw suction from the sump, which may sound a low-pressure alarm. This provides time for changing over to the standby strainer. Failure of this change over will result in pump's inability to supply lubricating oil to the engine, finally resulting in an engine failure, (Cicek & Celik 2013).These filters will be identical as shown in Fig. 4. The state diagram for the filters is shown in Fig. 5. The reliability functions an exponential function of time t and the failure rate λ expressed as number of failures per running hours , (Brandowski 2009; Navy 1994).

Figure 4. Lube oil suction strainers for the Main Engine Lube oil system

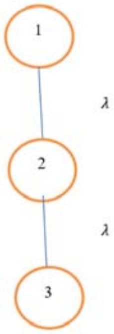


Figure 5. Markov Model analysis for the M.E. Lube oil Strainer S

Table 2. State of Lube oIl strainer S

State	Strainer 1	Strainer 2
1	Clean	Cllean
2	Clooged	Clean
3	Clogged (Failed)	Clogged(Failed)

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,

$$R_s(t) = e^{-\lambda t} \sum_{i=0}^{1} \frac{(\lambda t)^i}{i!}$$

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

2.2 *Reliability of the Main Engine Lube Oil System*

The state diagrams for all other components of the system are analysed on the same lines, as done for the suction strainer S. Markov analysis(Smith 2011; Troyer 2006), carried out to determine the reliability of the system components . Finally the relaiility of the lubricating oil system is determined,(Liberacki 2007)

$$R_{L.O.}(t) = R_s(t) R_p(t) R_F(t) R_{TCV}(t) R_{CLR}(t) \quad (2)$$

where
$R_p(t)$ is the reliability of the Pumps
$R_F(t)$ is the relaibility of the Filter
$R_{TCV}(t)$ is the reliability of the temperature control valve
$R_{CLR}(t)$ is the reliability of the cooler.

3 RELIABILITY OF SCAVENGE AIR SYSTEM

Reliability of a scavenge air system for a large propulsion engine consists mainly of an exhaust gas turbocharger, (Takashi and Susumu, 1994), (Conglin Dong 2013). The heat energy of the exhaust gas drives the exhaust gas turbine coupled to a rotary air compressor, which draws air from the engine room. The compressor compresses the air and then is cooled in an air cooler before being sent to the engine cylinder. One such turbocharger is shown in Fig.6. In short the turbocharger and the cooler form the main elements of the scavenge air system, failure of any one of the component could lead to failure of the main engine, as shown in the fault tree, (Zhu 2011), diagram in Fig.7.

Figure 6. Turbocharger for a large two stroke engine at test bed in QMD, Qungdao, China.

3.1 *Fault tree for Main Engine failure*

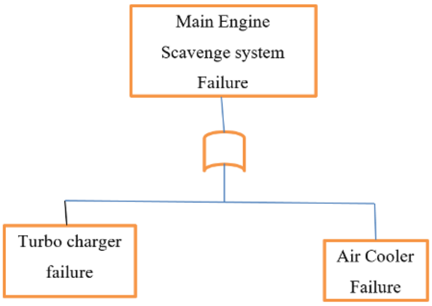


Figure 7. Fault tree for a Main Engine Scavenge system

Failure of either the Turbocharger, (ATSB,2006), or Air Cooler would result in failure of the Main Engine Scavenge system, (Laskowski 2015).

3.2 *RBD for Scavenge air system*

A reliability block diagram for the scavenge air system is shown below

$$R_{Scaveneg\ air} = R_{Turbocharger} * R_{Air\ Cooler}$$

Figure 8. RBD for Main Engine Scavenge system

The turbocharger and air cooler are in series, hence the reliability of the scavenge air system could be computed. These two components form a very robust part of the scavenge air system. Depending upon the engine capacity there could be one or more turbochargers or air coolers fitted to the main propulsion engine. This arrangement has more to do with the engine capacity and not based on a redundancy factor.

4.3 *Reliability of the Turbocharger*

The turbocharger assembly consists of air filter, blower casing, turbine casing, rotor and bearings,(Schieman 1992-1996). Modern turbochargers are manufactured with sleeve type bearings which have very high operating life ranging up to 50,000 running hours, (SE)Hence while determining the reliability of the turbocharger we need to look into the phase 3 of the bath tub curve where the end of life wear out could be considered, rather than the phase 1 or phase 2 of the bath tub curve. In the phase 3 the reliability of the Turbocharger may be computed using Weibull distribution, (Dhillon, 2002).The Reliability of the Turbocharger could be expressed as a function of time t.

$$R_{Airclr}(t) = e^{\left(-\frac{t}{\theta}\right)^{\beta}}$$

and the hazard rate function will be given by

$$\lambda_{Airclr}(t) = \frac{\beta}{\theta}\left(-\frac{t}{\theta}\right)^{\beta-1}$$

where θ is the scale parameter that influence both the mean and the spread or dispersion of the distribution and is the characteristic life and has units to those of time t, in this case hours, $\theta > 0$. β is referred as the shape parameter and $\beta > 0$. The Weibull hazard rate function can be increasing or decreasing depending on the value of β. If $\beta = 1$, $\lambda_{Turbo}(t)$ is constant and equal to $1/\theta$,the distribution being identical to the exponential.

3.3 *Reliability of the Air cooler*

The air cooler plays a very vital role in the scavenging system. The high temperature air discharged by the turbocharger needs to be cooled before sending it to the engine cylinders. These air coolers are generally sea water cooled, the sea water being passed through bronze alloy tubes, by means of a two pass cooling arrangement, to provide effective cooling of the charge air. The air flow will be one pass through the aluminium fins which are soldered to the brass alloy tubes, to avoid excessive pressure drop. Considering the reliability of the air cooler we should again consider the aging factor, hence we will be considering the phase 3 of the bath tub curve. On similar lines to detecting reliability of the turbocharger, the reliability of the air cooler may be computed using Weibull distribution, (Kiriya 2001). The reliability of the air cooler could be expressed as a function of time t.

$$R_{Airclr}(t) = e^{\left(-\frac{t}{\theta}\right)^{\beta}}$$

and the hazard rate function will be given by

$$\lambda_{Airclr}(t) = \frac{\beta}{\theta}\left(-\frac{t}{\theta}\right)^{\beta-1}$$

where θ is the scale parameter that influence both the mean and the spread or dispersion of the distribution and is the characteristic life and has units to those of time t, in this case hours, $\theta > 0$. β is referred as the shape parameter and $\beta > 0$.

3.4 *Reliability of the Scavenge air system*

The turbocharger and air cooler being in a serial configuration, both needs to function for the scavenge air system to function. Both the components are critical and if either one of them fails the scavenge system will fail. The combined Weibull system reliability can be computed as below

$$R_{scavenege\ air} = \prod_{i=1,2} e^{-(t/\theta_i)^{\beta_i}} \tag{3}$$

where i=1 is the Turbocharger and i= 2 is the Air cooler.

4 RELIABILITY OF THE MAIN PROPULSION ENGINE

We have determined the Reliability of the Fuel oil system by Markov analysis, Lubricating Oil system by Markov analysis which are both modelled using constant failure rate principle, and also determined the Reliability of Scavenge air system as a time dependent failure model, we are now positioned to determine the Reliability of the Main propulsion engine as follows:

$$R_{MainEngine} = \prod R_{iI=1,2,3,} \tag{4}$$

i=1 is the fuel oil system from Equation1 (Markov modelling)
i=2 is the lubricating oil system from Equation2 (Markov modelling)
i=3 is the scavenge air system from Equation3 (Weibull modelling)

5 IMPROVING RELIABILITY

Reliability of the main engine can be improved by improving the individual system reliability as seen in the above Equation 4 above, For instance in the case of the scavenge air system, a modern high performance turbocharger will improve the reliability of the turbocharger.This cost for improvement of reliability need to be assessed and the cost benefit for the incremental reliability to be determined. If the original value of reliability R_O at cost x is improved to Reliability R_I at cost y, then the incremntal reliability for the differential cost $\frac{R_I - R_O}{y - x}$ should be compared with the base relaibility to cost ratio which in this case is $\frac{R_O}{x}$.

For cost benefit $\frac{R_I - R_O}{y - x} > \frac{R_O}{x}$.

This could be a feasible proposition for some components, but not for all components. Also we could look at an appropriate maintenance program to strike the right balance between reliability required and the cost penalty likely to be incurred. I would like to draw attention to the air cooler in the scaveneg air system as an example. All modern air coolers manufactured by major engine manufactureres have a cleaning in place system incorporated for maintenance of air coolers, which involves no dismantling of the air cooler whilst carrying out maintenance,(Dhillon 2002). Accordingly the maintenance intervals for air coolers could be shorter, at the same time increasing the maintenance intervals of turbochargers and stil provide a more effcient and reliable main engine.

6 CASE STUDY OF TURBOCHARGER FAILURE ON A MERCHANT VESSEL

We shall study an intertsing case study of a main engine turbocahrger failure of which could lead to disastrous consequenes, resulting in stoppage of a main engine at sea. Turbochargers play a great role in the opeartion of the main engine, Hence reliaility of the main engine is depenedent to a large extent on the reliability of turbochargers,(Heim 2002). An important factor to be taken into consideration is the matching of the turbocahrger to the main propulssion engine, (Hountalas 2000). Since the main propulsion slow speed engine and the turbochargers are normally manufactured by two different manufacturers, who are expert in their own field, it is inevitable that there could be an issue on the conceptual thinking between the two parties. However any matching discrepancies need to be sorted out during the ship's sea trial. Any mismatch could be corrcetd by replacment of the diffuser or nozzle ring,(Kim et al. 2009)

The case study refers to a vessel out at sea and the inestigation as carried out by the Australian Transport safety Bureau, (Australian Transport Safety Bureau 2006,). The investigation refers to a bulk carrier powered by a large twos stroke engine with a rated power of 6400 kW, propelling at 14.5 knts. The vessel suffered srious damge due to failue of the turbocharger, on two ocasions within a span of less than 5 months. The exact cause of the damage was not available, but in both th cases the failure followed a large engine scavenge fire. The figure 9 below show the extent of the serious damage to the turbocharger rotor, resulting in immobilisation of the main engine, (Takashi 194).

Figure 9. Damaged turbocharer rotor shaft (Courtesy : ATSB Investgation 186 and 191)

7 CONCLUSION

In this paper we have looked at methods of determining the reliability of three subsystems of a vessel’s main engine which includes the fuel oil system, lubricating oi system and the scavenge air system. The fuel oil and lubricating oil sytem was modeleld by Markov analsis and the scaveneg air system was analysed using Weilbull distribution which is time dependent failure model. An attempt has been made to make reliability assessment of vessel’s main engine by combining Markov analysis integrated with time dependent failures.We have also discussed the increamental reliability to increamental cost ratio for the main enginewhich should always be greater than the original reliability to original cost ratio, for cost benefits in the long run. Finally we looked at some examples of effectively altering the maintenance intervals of certain system components, whwerby the overall reliability of the system could be improved.

A case study of turbocharger failure on a mercahnt vessel was studied and it was shown that the turbocharger failure can have a major impact on the main engine operation, leading to imobilisation of the main engine.Hence matching of the turbocharger and main engine is very critical for safe and reliable operation of the main engine.

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