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Failure trends and reliability analysis of patrol boat propulsion system components. Case study of Libyan Navy patrol boat

تحليل اتجاهات الأعطال ووثوقية مكونات منظومة الدفع لزورق دورية. حالة زورق دورية للبحرية الليبية

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Abstract

The availability of patrol boat is significantly influenced by the reliability of its propulsion system $R_s(t)$. Key components of this system, including the main prime movers, generator sets, auxiliary machinery, and steering gear, are essential to the vessel's operational performance. These subsystems exhibited increasing failure rates. The study examines history of failures over 6,658 hours of seagoing duty, with an analysis of failure trends to determine failure rates (λ) and the mean time between failures (MTBF). Additionally, the study estimates the reliability of critical propulsion system components and develops a reliability calculator using Microsoft Excel. The analysis identifies a prevalent failure mode in the three main engines, characterized by black exhaust, which results in power loss, increased fuel consumption, and progressive engine deterioration. Fault Tree Analysis (FTA) method, facilitated by Isograph software, is employed to investigate and predict the underlying causes of black exhaust failure in the main engines. The findings of this research provide valuable insights for enhancing propulsion system reliability through the optimization of maintenance strategies, ultimately improving the operational lifespan and performance of patrol boats.

Keywords: Reliability, MTBF, fault tree analysis FTA, failure rate, black smoke.

الملخص

تتأثر إتاحة زورق الدورية بدرجة كبيرة بوثوقية منظومة الدفع $R_s(t)$. تعد المحركات الرئيسية ومجموعات المولدات والآلات المساعدة ومعدات التوجيه من المكونات الأساسية لمنظومة الدفع وللأداء العملياتي للزورق. تعرضت هذه المكونات لمعدلات اعطال متزايدة. في هذه الدراسة تم تجميع تاريخ وحالات الاعطال خلال 6,658 ساعة من العمل في البحر، وتحليل اتجاهات ومعدلات الفشل والزمن الوسطي بين حالات الفشل (MTBF)، وتقدير وثوقية المكونات المهمة لمنظومة الدفع للزورق وإنشاء حاسبة الوثوقية باستخدام الجداول الإلكترونية. بالإضافة إلى ذلك، تبين أن العطل الشائع في المحركات الرئيسية الثلاثة هو غاز لعادم الأسود الذي يؤدي إلى فقدان القدرة وزيادة استهلاك الوقود، بالإضافة إلى التدهور السريع للمحرك. باستخدام برنامج isograph تم استخدام طريقة تحليل شجرة الأعطال (FTA) للفحص والتنبؤ بأسباب حدوث الدخان الأسود من العادم في المحركات الرئيسية. يمكن الاستفادة من النتائج القيمة التي تم الحصول عليها لتحسين وثوقية منظومة الدفع من خلال تحسين نظام الصيانة المقدم خلال عمر الاستخدام للمحرك.

الكلمات المفتاحية: الوثوقية، الزمن الوسطي بين الأعطال، تحليل شجرة الأعطال، معدل الأعطال، دخان أسود.

1. Introduction:

Operational availability of navy vessels are very essential factor for the navy in order to have done their sensitive role in protecting the state territorial waters. Reliability of ship prolusion system is the main factor influencing the operational availability of naval vessels. Reliability R(t) is defined as the probability that system (component) will function over some time period (t) [8] and it is inversely proportional to failure rete λ.

System and component reliability is an indication of maintenance efficiency provided. The initial scope of this paper is to determine the reliability of propulsion system In order to improve maintenance strategies adopted by navy technical department and maintenance practice applied by vessel's crew. Reliability and maintainability engineering provide new concepts and tools such as; fault tree analysis (FTA), failure mode effect criticality analysis (FMECA) and accelerated life test for enhancing assets performance and life cycle cost reduction, Patrol boat propulsion system is complex, in which components are combined series-parallel and redundant system. Reliability of such systems usually is high. Due to obsolescence and lack of preventive maintenance, the propulsion system has exhibited high failure rate. The need for tracing history of failure trends and reliability analysis of patrol boat power plant components.

In this paper fault tree analysis (FTA) method with Isograph software is used to analyze the most occurring failure in the patrol boat propulsion system. FTA is a deductive analysis approach for resolving an undesired event into its causes, looking backward at the causes of a given event, using specific logic in the process and specific symbols to illustrate event relationship [7]. Important benefits of FTA are:

- To exhaustively identify the causes of a failure.
- To identify weaknesses in a system.
- To prioritize contributors to failure.
- To quantify the failure probability and contributors.
- To optimize tests and maintenances.

2. Literature review:

Evaluating failures in a ship's propulsion system results in high costs and the loss of prestige for the company. Land/sea fleet employees need to detect and minimize the failures that may occur in ship propulsion systems in advance to ensure the continuity of the ships' operations. In a study by (Zonguldak et.al.) [1], the recorded failure data of four different ships belonging to a fleet in the last 10 years are used. Failures were examined as a whole since the ships have similar propulsion

systems. The obtained failure data were grouped, and the average time to fix the failures was determined and made suitable for reliability, availability, and maintainability (RAM) analysis. A suitable model was created for grouped failures by Isograph's RWB software. As a result of the analysis of the propulsion system and its subsystems, the main engine of the ship was shown to

have the best reliability. Furthermore, the most important components were the cylinders of the main engine as subsystems. This study highlights the components that are important to the reliability of a propulsion system.

(Zhibin W. et al.) in their study [2] described the common fault diagnosis method of diesel engine, the development trend of diesel engine fault diagnosis technology is predicted after analyzing the common fault diagnosis method. There is a variety of methods for condition monitoring and fault diagnosis of diesel engine, some of which were introduced briefly, such as oil analysis method, vibration noise method, performance parameter diagnosis method, instantaneous speed method.

The reliability of marine propulsion systems depends on the reliability of several sub-systems of a diesel engine. The scavenge air system is one of the crucial sub-systems of the marine engine with a turbocharger as an essential component. (Vlatko K. et al.) [3] analyzed the failures of a turbocharger through the fault tree analysis (FTA) method to estimate the reliability of the system and to predict the cause of failures. They used a quantitative method for assessing the probability of faults occurring in the turbocharger system. The main failures of a scavenge air sub-system, such as air filter blockage, compressor fouling, turbine fouling, cooler tube blockage and cooler air side blockage, are simulated on a Wärtsilä-Transas engine simulator for a marine two-stroke diesel engine. The results obtained through the simulation can provide improvement in the maintenance plan, reliability of the propulsion system.

The aim of the study by (Kritonas D. et al.) [4] is to investigate the safety enhancement of a cruise ship lubricating oil system by employing safety, reliability, availability and diagnosability analyses, which are based on the system functional modelling implemented in the MADe software. The safety analysis is implemented by combining a Failure Modes, Effects and Criticality Analysis and the systems functional Fault Tree Analysis. Subsequently, Reliability Block Diagrams are employed to estimate the system reliability and availability metrics. The MADe toolbox for determining sensors locations is employed for a more advanced diagnostic system development. A number of design modifications are proposed and the alternative configurations reliability metrics are estimated.

Another research (Konstantinos D. et al.) [5] contributes in the creation and initial implementation of a probabilistic multi-component prognostic Condition Monitoring model for ship machinery and equipment maintenance scheduling. Systems involved include engine internal and external components, starting, cooling, and lubrication and control monitoring systems.

The overall reliability performance of these sub-systems and the entire main engine is suggested. Moreover, the study presented the components and failure types' layout arrangement of engine internal and external sub-systems as well as the overall reliability performance of the sub-systems.

3. Methodology:

Propulsion system of the patrol boat consists of four main diesel engines; each develops 4500hp, three generator sets, auxiliary machinery with various systems and propeller shafts. The reliability of a propulsion system $R_s(t)$ is primarily influenced by the individual reliability $R_i(t)$ of its components, which in turn is determined by the failure rates of these components. This study focuses on analyzing the failure trends and overall reliability of the power plant components aboard Libyan Navy patrol boat.

The core elements of propulsion system are main engines, their reliability depends mainly on the preventive maintenance provided [8]. Manufacturer of these engines highly insists to follow the maintenance time schedule, table (1).

3.1. Data analysis:

The analysis is based on operational data collected over a total of 6,658 hours of seagoing duty. During this period, 21 different failures were recorded across various components of the power plant. The failures were distributed among four main diesel engines used for ship propulsion, three power generators, the steering gear, the air system, and the fresh water system. Notably, no serious failures had been recorded for other components of the propulsion system.

Table (1). Maintenance time schedule for main diesel engines

Application group	Maintenance Stage															
	W1	W2			W3			W4			W5			W6		
	on each operating day	after Operating hours	each Limit value		after Operating hours	each Limit value		after Operating hours	each Limit value		after Operating hours	each Limit value		after Operating hours	each Limit value	
			months	years		months	years		months	years		months	years		months	years
1D S	x	150	6		300		1	1500		2	3000		6	6000		12

3.2. Component reliability:

Failure trends are analyzed to determine the failure rates (denoted as λ) and mean time between failures (MTBF) for each component. Using these data, by excel sheet a reliability calculator is developed for each of power plant component. For the purposes of this study, it is assumed that the failure distribution of each component follows an exponential distribution, which is commonly used for modeling the reliability of mechanical systems. Component reliability $R_i(t)$ and *MTBF* can be calculated as shown below (8).

$$R(t) = e^{-\lambda t} \quad (1)$$

$$MTBF = \int_0^{\infty} R(t)dt = \frac{1}{\lambda} \quad (2)$$

3.3. Top event and fault tree analysis (FTA):

It is evident that, the most occurring failures in all main prime movers are related with black exhaust gas; therefore, by using Isograph reliability workbench software, fault tree analysis (FTA) method was conducted to determine the probability of curing the cause of black exhaust gas. The FTA method [7] is a graphical model of the various combinations of faults that will result in the occurrence of the predefined undesired event. In this case, mainly air supply system, fuel engine system, exhaust system and engine itself could be the cause of black exhaust gas or at least one of them. Probability of black exhaust failure is estimated. Fault tree analysis steps are:

- An undesired event is defined.
- The event is resolved into its immediate causes.
- This resolution of events continues until basic causes are identified.
- A logical diagram called a fault tree is constructed showing the logical event relationships.

4. Results and discussions:

4.1. Reliability data analysis:

Using fleet records, during a total of 6658 hours of sea going duty, Libyan navy patrol boat had exposed to 21 serious failure as shown in table (2). Fifteen of these failures were related to four main engines. Power generator sets had two failures and air system two failures, while steering gear and fresh water system had only one failure for each. Failure rate (λ) is a result of dividing number of failure by working hours. Mean time between failures MTBF is a multiplicative revers of failure rate λ, equation (2). Diesel engines had the highest failure rate while fresh water system, steering gear and generator sets had less failure rates.

Table (2). Propulsion machinery data and failure history

	Working hours	No. of failures	λ	MTBF (hr)
DE1	1451	3	0.002	500
DE2	1542	6	0.004	250
DE3	1682	5	0.003	333
DE4	938	1	0.001	1000
Gen. 1	585	0	0	-
Gen. 2	1809	1	0.0005	2000
Gen. 3	2234	1	0.0004	2500
Steering G	6658	1	0.00015	6667
Air sys.	6658	2	0.0003	3333
Fresh W. S.	6658	1	0.00015	6667

4.1.1. Main prime movers reliability:

By using, excel sheet, reliability calculators for propulsion system components created, it is evident that, results exhibit sharp decline of reliability of all components with little differences. Main engines had the lowest reliability table (3), as shown in figure (1). Even though, the real service time for main engines without major overhauling is more than fifteen years, the factual working hours for all engines is very low. According to the maintenance plan recommended by the manufacturer table (1), twelve years of service should be met with at least 6000 working hours until the major overhaul. In this case failure rates depends on working hours and time spent without providing W5 and W6 maintenances which leads to increase dormant failures.

4.1.2. Generator sets reliability:

There are three generator sets supplying electricity power for the patrol boat. Usually two of them working in sharing mode, the third is standby therefore they had little difference in failure mode. Two generator sets exhibited sharp reliability declination table (4), as shown in figure (2). Generator number one had run for 585 hours without any failures, while generator no.3 had better reliability than generator no.2.

Table (3). Reliability calculator for Diesel engines

t	$R_{DE1}(t)$	$R_{DE2}(t)$	$R_{DE3}(t)$	$R_{DE4}(t)$
0	1	1	1	1
250	0.60653066	0.367879441	0.472366553	0.778800783
500	0.367879441	0.135335283	0.22313016	0.60653066
750	0.22313016	0.049787068	0.105399225	0.472366553
1000	0.135335283	0.018315639	0.049787068	0.367879441
1250	0.082084999	0.006737947	0.023517746	0.286504797
1500	0.049787068	0.002478752	0.011108997	0.22313016
1750	0.030197383	0.000911882	0.005247518	0.173773943
2000	0.018315639	0.000335463	0.002478752	0.135335283
2250	0.011108997	0.00012341	0.00117088	0.105399225
2500	0.006737947	4.53999E-05	0.000553084	0.082084999
2750	0.004086771	1.67017E-05	0.000261259	0.063927861
3000	0.002478752	6.14421E-06	0.00012341	0.049787068
3250	0.001503439	2.26033E-06	5.82947E-05	0.038774208
3500	0.000911882	8.31529E-07	2.75364E-05	0.030197383
3750	0.000553084	3.05902E-07	1.30073E-05	0.023517746
4000	0.000335463	1.12535E-07	6.14421E-06	0.018315639
4250	0.000203468	4.13994E-08	2.90232E-06	0.014264234
4500	0.00012341	1.523E-08	1.37096E-06	0.011108997
4750	7.48518E-05	5.6028E-09	6.47595E-07	0.008651695
5000	4.53999E-05	2.06115E-09	3.05902E-07	0.006737947

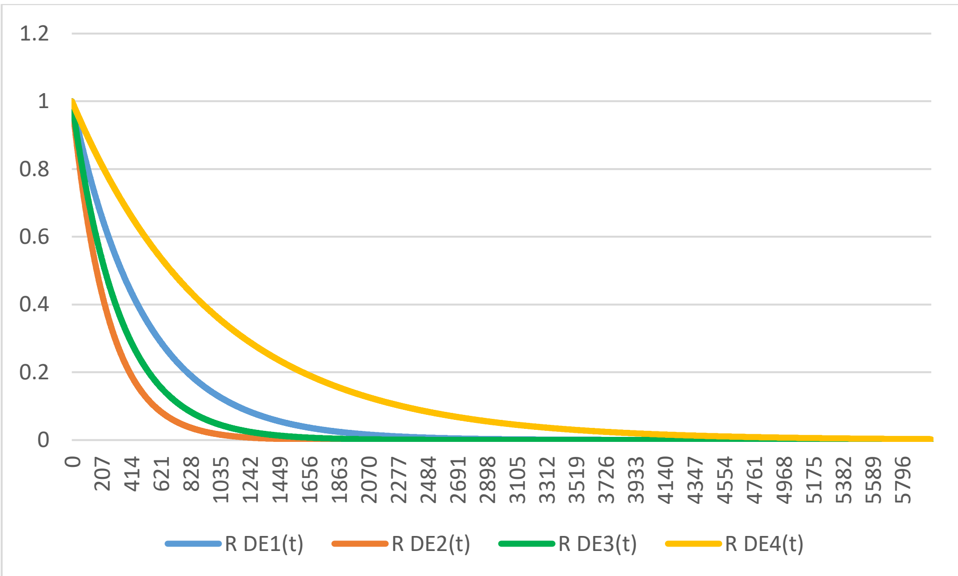

Fig (1). Main diesel engines reliability diagram

Table (4). Generator sets, steering gear and air system Reliability calculator

Time hrs.	R(t)			
	Gen. 2	Gen. 3	Steering gear	Air sys.
0	1	1	1	1
250	0.882496903	0.904837418	0.963194418	0.927743486
500	0.778800783	0.818730753	0.927743486	0.860707976
750	0.687289279	0.740818221	0.893597347	0.798516219
1000	0.60653066	0.670320046	0.860707976	0.740818221
1250	0.535261429	0.60653066	0.829029118	0.687289279
1500	0.472366553	0.548811636	0.798516219	0.637628152
1750	0.41686202	0.496585304	0.769126364	0.591555364
2000	0.367879441	0.449328964	0.740818221	0.548811636
2250	0.324652467	0.40656966	0.713551975	0.509156421
2500	0.286504797	0.367879441	0.687289279	0.472366553
2750	0.252839596	0.332871084	0.661993197	0.438234992
3000	0.22313016	0.301194212	0.637628152	0.40656966
3250	0.196911675	0.272531793	0.614159876	0.377192354
3500	0.173773943	0.246596964	0.591555364	0.349937749
3750	0.153354967	0.22313016	0.569782825	0.324652467
4000	0.135335283	0.201896518	0.548811636	0.301194212
4250	0.119432968	0.182683524	0.528612304	0.279430968
4500	0.105399225	0.165298888	0.509156421	0.259240261
4750	0.093014489	0.149568619	0.490416622	0.240508463
5000	0.082084999	0.135335283	0.472366553	0.22313016

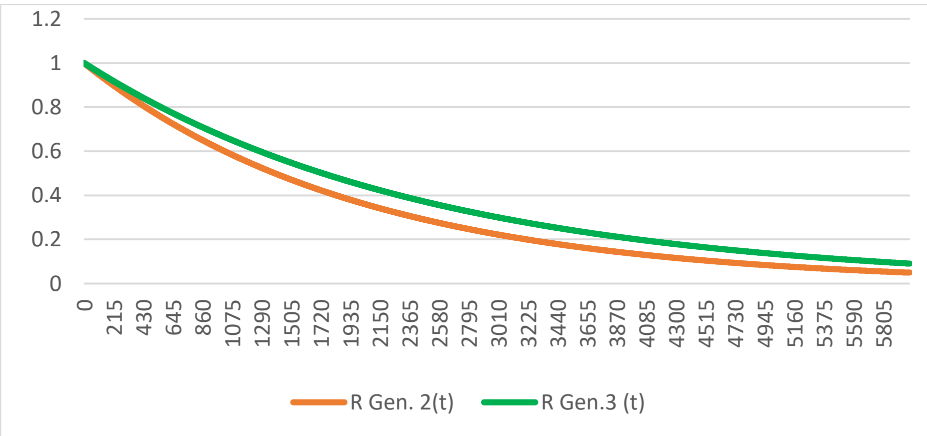

Fig (2). Reliability diagram of generator sets no.2 and 3

4.1.3. Reliability of steering gear and air system:

Steering gear function is to secure boat maneuverability, while air system role for stating main prime movers and control in addition, to auxiliaries. Reliability calculator for steering gear and air system is demonstrated in table (4). Reliability diagram is illustrated in figure (3). In spite of low reliability of steering gear, yet still it had the best reliability of all propulsion system components followed by air system.

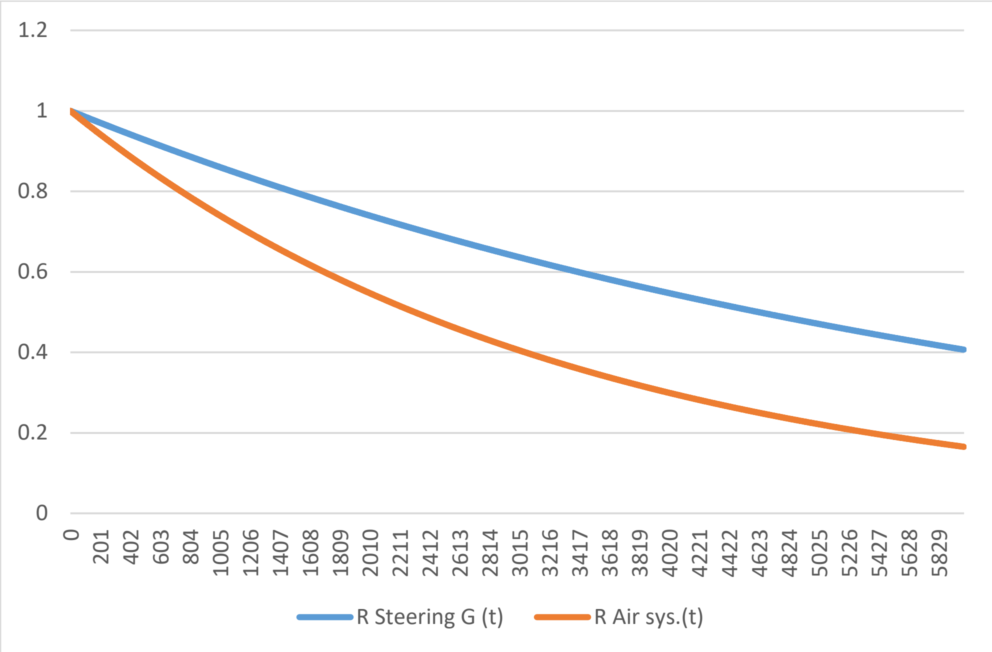

Fig (3). Steering gear and air system reliability.

4.2. Fault tree analysis for diesel engine black exhaust gas:

Diesel engine may continue to operate in a degraded mode following certain type of failures. It may continue to perform its function but not at specified operating level. The case of black exhaust gas is dominant in three of four main engines. Whether the degraded mode is considered a failure or not must be determined as part of reliability specification. The applied method for fault detection is the fault tree analysis FTA. When creating a fault tree by using Isograph software, it is necessary to define the causal connections between events (failures) of the analyzed system, identify all possible faults that can cause the top event to happen. In this case, causes of black exhaust gas could be at least one of; air supply, engine, exhaust system or fuel system. In our case, we have top event, four intermediate event, nine basic events and three undeveloped events. Table (5) shows six events with failure rates more than zero that could cause black exhaust gas. In addition, there are other six basic and undeveloped events with zero failure rates.

Table (5). Events with failure rates

System	Fuel system		Engine	Exhaust system	Air supply	
Subsystem	Unit injectors defective	Excessive fuel injection	Valve not closed	Piping contaminated	Air filter clogged	Intercooler clogged
	Dies. 1	Dies.1	Dies. 3	Dies. 3	Dies. 2	Dies. 2
Event	Basic	Undeveloped	Basic	Basic	Basic	Basic
Failure rate	0.0002	0.0001	0.0004	0.0001	0.0003	0.0001

Failure rates are used by means of Isograph software to build black exhaust gas fault tree as illustrated in figure (4) to determine the probability of occurrence exhaust gas in main diesel engine. Data in table (6) are failure rates for back exhaust gas which are probabilities of the basic events used as inputs in the Isograph software.

Table (6). Input data for Isograph software

	A1	A2	A3	B1
Basic events	Incorrect injection timing	Unit injectors defective	Excessive fuel injection	Engine over loaded
Probability	0.0	0.0002	0.0001	0.0
	B2	B3	B4	C
Basic events	Incorrect governor setting	Burner defective	Valve not closed	Exhaust piping contaminated
Probability	0.0	0.0	0.0004	0.0001
	D1	D2	D3	D4
Basic events	Charging pressure too low	Air leaking	Air filter clogged	Intercooler clogged
Probability	0.0	0.0	0.0003	0.0001

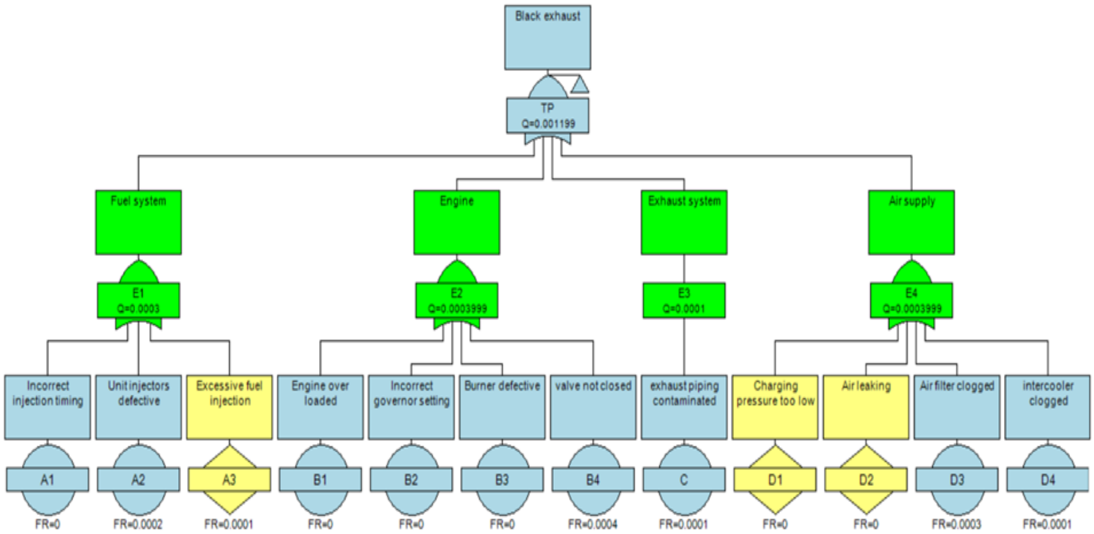

Fig (4). Black exhaust gas fault tree

The aim is black to determine the probability of occurrence exhaust gas in main diesel engine *P(TP)*. First determine the of occurrence probability of intermediate events $P(E_1)$, $P(E_2)$, $P(E_3)$ and $P(E_4)$, as illustrated in figure (4).

Table (7). Probabilities of intermediate and top events

Event	E_1	E_2	E_3	E_4	TP
Subsystem	Fuel system	engine	Exhaust system	Air supply	
Probability	0.0003	0.0003999	0.0001	0.0003999	0.001199

Results of fault tree analysis is introduced in table (6), probability of top failure is relatively high. Engine and air supply system are the highest probable failure modes, followed by the fuel system, whilst, the exhaust system is the lowest failure mode. Usually, causes of such failures are due to inefficient maintenance provided.

5. Conclusion:

The reliability of boat propulsion system depends on the reliability of each component in the system. The aim of this study is to analyze failure trends and reliability of critical components in the propulsion system. In general, the outcome introduced sharp decline of reliability through life span of the patrol boat. By following the root causes of most occurring failure which is the black exhaust gas, almost all related subsystems contribute to an increase to the failure rate. In such cases, the causes are related to deficiencies of maintenance strategy provided.

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