RAM methodology application to outboard

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Abstract

The market share of the outboard engines is increasing in the maritime engines market. Outboard engines are used in critical situations and a failure could jeopardise users. Hence, it is necessary to improve the reliability of this engines. Performing a Reliability, Availability and Maintainability (RAM) analysis is crucial in order to study the service performance of the engines. Part of the study includes the application of the failure modes effects and criticality analysis (FMECA), which is a step-by-step approach for identifying all possible causes of failures and its effects in designing, manufacturing and assembly process on the engines. In this paper, the FMECA analysis was applied on the engines in order to identify and prioritize by probability of occurrence, detectability and severity, the failures encountered in the workshops, accordingly to the calculated Risk Priority Number (RPN). In addition, corrosion tests were performed because corrosion effects are often a cause of failures. To understand better the process, three different tests were performed. The first consists in studying the behaviour of the current circulating between the anode and the engine for different engine speeds. The second test consists in calculating the corrosion rate in the anode when paired with the engine in static conditions. The last one involves studying the behaviour of the engine potential for different area ratios of the anode and the motor. The results of this analysis could be used to improve the design and maintenance procedures of the outboard engines.

Keywords: RAM, FMECA, RPN, Corrosion testing, Corrosion rate

1. Introduction

The increased competition imposed by globalization and the need to meet the boat performance requirements of professional and recreational users, led to a constant necessity to optimize and improve marine engines as regards reliability and an acquisition and operating costs reduction. The outboard engines market in Europe is very competitive with only six brands, in which two of them represent more than half of the sales. In this way, Yamaha has always been proposing new technologies in order to stand out from the competition. Yamaha is the brand that bets the most on the service component and after-sales procedures, these being the prominent aspects that are recognize by the nautical community. Therefore, all maintenance procedures and product analysis are of great importance to the company in order to increase the Yamaha market share.

Risk assessment integrates reliability and hence it can be used as a guideline and decision tool to identify and reduce the risk of a certain failure by improving the maintenance procedures or redesigning the component/equipment. In this analysis, failure modes, effects and criticality analysis are used as a risk assessment technique, which serialize the failures in order to prioritize the resolution of the most critical failures.

Throughout failure modes analysis it was found that corrosion is a problem that occurs very frequently in boats and engines of every brand. In order to understand the corrosion process in the outboard engines, some corrosion tests were performed in order to study the behaviour of current, potential, corrosion rate and compare it to existing results.

2. Concepts Review

RAM and FMECA

RAM refers to Reliability, Availability and Maintainability. Reliability is the probability of survival after the component/system operates for a certain period of time. Maintainability describes how soon the component/system can be repaired and determines the up and down time patterns. Availability is the percentage of time that the system is working without any problem [1]. RAM analysis process is an association of methods and integrative concepts based on the results obtained for the control of technical risks and which makes it possible to have a guarantee that the system meets the project requirements in terms of reliability, availability and maintainability. RAM analysis can identify potential causes of failures and develop mitigation solutions in an effort to minimize its risk. In order to identify and prioritize the failures, a complementary method should be used [2]. The FMECA (Failure modes, Effects and Criticality analysis) could be used in this part of the process [3]. This analysis not only gathers the information of the failures modes but also sets the importance of each failure, with the help of calculated Risk Priority Number (RPN) [4]. This RPN is calculated with variables that represent the frequency of occurrence, severity and detectability of the failure. The ratings for each parameter of RPN are adapted to different situations. The FMECA analysis should follow the following steps:

- Step 1 – Brainstorm about potential failures modes;
- Step 2 – List potential effects of each failure mode;
- Step 3 – Assign a severity (S) ranking for each effect;
- Step 4 – Assign an occurrence (O) ranking for each failure mode;
- Step 5 – Assign a detection (D) ranking for each failure mode/effect;
- Step 6 – Calculate the risk priority number (RPN) for each failure mode.

$$RPN = S \times O \times D$$

By the end of the process, all of the information gathered of the failures modes and risk should be organized in a table, in order to allow easy and fast access to the information for future improvements.

Corrosion

Corrosion is a process of deterioration of a material due to the reaction with the surrounding environment, by chemical or/and mechanical action. In maritime environments, the process is much faster than in non-maritime environments because moisture and salts are present in a greater concentration [5].

Galvanic corrosion is the corrosion process that results from the difference in potential between to different metals that are submerged in an electrolyte. The process becomes more favourable from the thermodynamically point of view, as the potential difference between the metals becomes greater. The corrosion of the most noble metal is reduced and the corrosion of the less noble metal is increased. This process could be used as a counter-measure for corrosion. A sacrificial anode could be electrically connected to the metal that should be protected. In practical terms, the potential of the noble metal should be reduced to a certain value. This reduction is controlled not only by the difference in potential of the metals connected but also by the ratio of the areas of the cathode and the anode. The manufactures define the potential between the set of the motor-anode and to a reference electrode that should be kept, in order to protect the motor from corrosion [6].

3. Case Study

RAM and FMECA

The failures were surveyed through questionnaires done by Yamaha dealers who provide repair services to outboard engines, as they are the ones who carry out engine verifications every day.

To classify the failures within the risk parameters, in this analysis the following Severity, Occurrence and Frequency criteria were used:

Table 1: RPN criterias ratings

Index	Frequency of Occurrence	Severity	Detectability
	Range (%)	Description	Description
1	0<Freq<10	None	Almost Certain
2	10<Freq<20	Very minor	Very high
3	20<Freq<30	Minor	High
4	30<Freq<40	Very low	Moderately high
5	40<Freq<50	Low	Moderate
6	50<Freq<60	Moderate	Low
7	60<Freq<70	High	Very low
8	70<Freq<80	Very high	Remote
9	80<Freq<90	Hazardous with warning	Very remote
10	90<Freq<100	Harzardous without warning	Absolutely impossible

Subsequently, the RPN could be calculated for each failure using the following expression:

$$RPN = F \times S \times D \tag{3.1}$$

Based on the RPN, were created three levels of severity that are expressed in the following table.

Table 2: Risk levels

Risk	RPN value
Low	RPN < 75
Medium	75< RPN <150
High	RPN > 150

RAM

The reliability and availability were calculated based on the existing preventive maintenance procedures and the failures normally encountered by the mechanics in the repairs and maintenances performed. For the present analysis, all of the components were considered to be in the normal life phase so that the failure rate could be considered constant during the time. The reliability of each component was calculated as having a mission of one thousand engine hours.

Corrosion testing

Three tests were performed in order to understand better the corrosion process on the outboard motors. All of the tests were performed in a tank with added salt in 3,5% concentration in an attempt to simulate the sea water, as the sea water represents the most aggressive conditions encountered by the outboard engines in normal usage. The anode used during the analysis is connected to the lower unit of the engine.

The objective of the first test was to determine the current that flows between the anode and the engine for different rpms of the engine. For this test, all of the contact points between the engine and the anode were isolated with epoxy, only allowing the current to flow between a cable connected to the ammeter and on the other side connected to the motor.

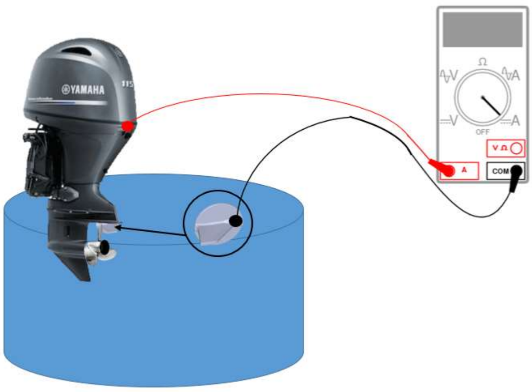

Figure 1: Test assembly for the current measures

The second test, consist in quantifying the corrosion/penetration rate of the anode when connected to the engine for a period of thirty-one days. The anode mass was measured before and after the test in order to know its variation. The area exposed is also a variable that should be known. The exposed area's value was calculated using a 3D scanner (EinScan-Pro). To calculate the corrosion rate is used the formula (3.2).

$$Corrosion/Penetration\ \ Rate\ = \frac{\mathrm{m}}{\rho \mathrm{At}} \tag{3.2}$$

The Faraday's law could also be used to calculate the corrosion/ penetration rate using the formula (3.3)

$$Corrosion/Penetration\ Rate = \frac{ia}{n\rho} \tag{3.3}$$

The objective of the third test was to study the behaviour of the area ratio variation between the anode and the cathode. To measure the potential, Calomel reference electrode was used. The engine area exposed was maintained constant, having the electrode exposed area changed during the four measures done in this test.

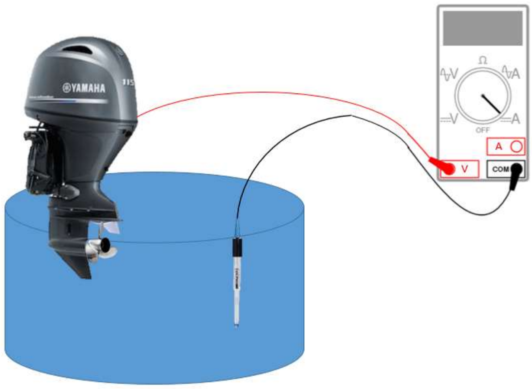

Figure 2: Test assembly for the potential measures

4. Results

RAM and FMECA

The results from the Reliability and Availability are summarized in the (table 3) for some of the outboard engine components.

Table 3: RAM values

Part	N.º of Part Failure	Failure Rate λ (h⁻¹)	Reliability $R(t) = e^{-\int_0^t \lambda(t)}$	MTBF (h)	MTTR (h)	Availability $\frac{MTBF}{MTBF + MTTR}$
Fuel Filter	3	$3{,}01 \times 10^{-4}$	73,94779%	100	2,5	97,6%
Gear oil	3	$3{,}01 \times 10^{-4}$	73,94779%	100	2,5	97,6%
Spark plugs	1	$3{,}34 \times 10^{-5}$	96,71946%	300	3,5	98,8%
Fuel pump filter	3	$1{,}0 \times 10^{-4}$	90,46561%	300	3,5	98,8%
O-ring fuel pump	1	$3{,}34 \times 10^{-5}$	96,71946%	300	3,5	98,8%
Water pump impeller	4	$1{,}34 \times 10^{-4}$	87,48614%	300	3,5	98,8%

Water Pump	3	$6{,}01 \times 10^{-5}$	94,16966%	500	4	99,2%
Timing Belt	3	$3{,}00 \times 10^{-5}$	97,042806%	1000	5	99,5%

The risk priority number calculated from the collected information is shown in the table 4.

Table 4: RPN values

Failure	**Frequency of Occurrence**	**Severity**	**Detectability**	**RPN**
	1 (Rare) a 10 (Very frequent)	1 (none) a 10 (Very dangerous without warning)	1 (certainly detected) a 10 (impossible detection)	
Gears	1	9	9	81
Fuel Pump	5	7	6	210
Injectors	3	6	8	144
Vapor-separator	2	8	7	112
Thermostat	4	7	6	168
Water pump	4	7	8	224
Alternator/ Rectifier/ Regulator	2	5	4	40
Remote control cable	2	4	5	40
Hydraulic direction	1	7	4	28
Starter engine	2	8	5	80
Trim	4	6	2	48
Piston Rings	2	6	8	96

In the (figure) it’s shown the relative position of each failure with the three levels of criticality created.

Some of the FMECA results are summarized in the annexed table.

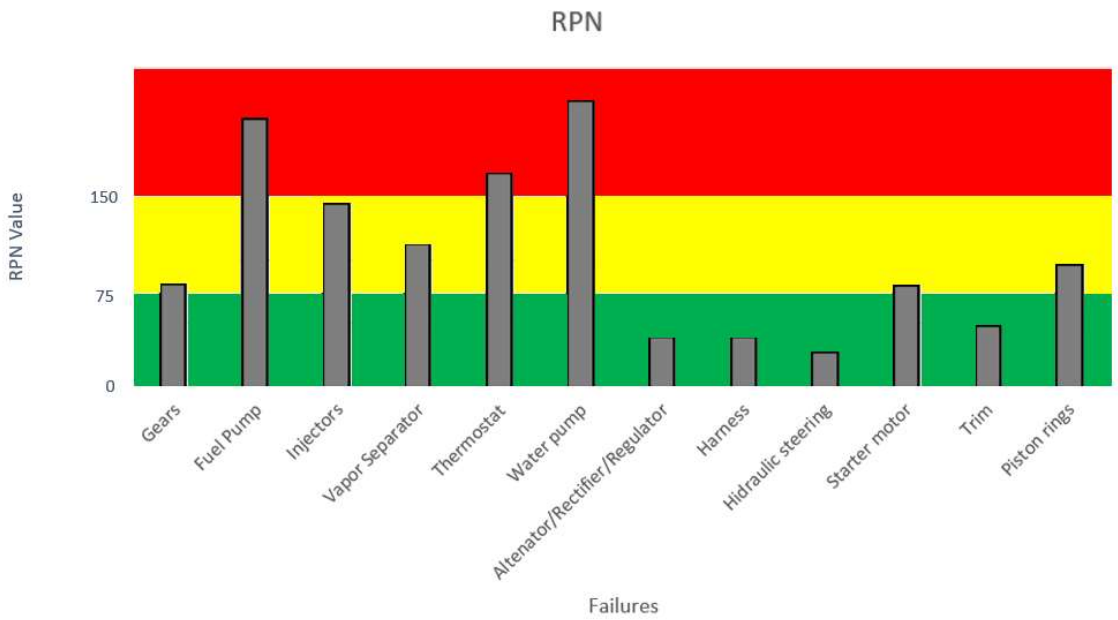

Figure 3: Failures with correspondent RPN level

Corrosion tests

The results from the determination of the current that flows between the anode and the engine for different rpms of the engine, are shown in the (table 5) and the behaviour of the variable is presented in the (figure 4).

Table 5: Current values obtained

Engine Rotation (rpm)	Current (mA)
0	49,2
750	79,2
900	74,1
1200	84,0
1700	90,4
2000	97,7
2500	99,8

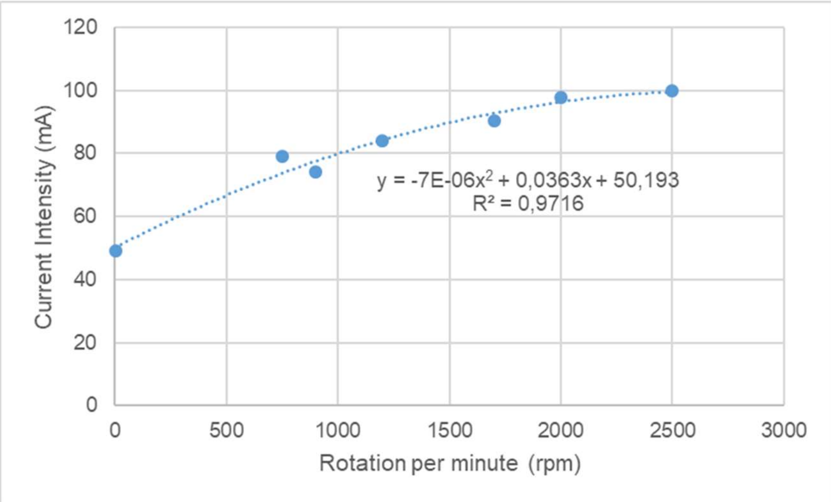

Figure 4: Current intensity tendency for different engine speeds

In order to compare the values, the current values should be divided by the exposed area so that we get the current density for the anode and the cathode. The cathode area was $195\,260\ \mathrm{mm}^2$ and anode area was $21\,468\ \mathrm{mm}^2$.

Table 6: Current Density for anode and cathode

Engine Rotation (rpm)	Engine Current Density (A/m^2)	Anode Current Density (A/m^2)
0	0,25	2,29
750	0,41	3,69
900	0,38	3,45
1200	0,43	3,91
1700	0,46	4,21
2000	0,50	4,55
2500	0,51	4,65

The typical range for a zinc anode is around 0.5 – 2.0 $\mathrm{A/m^2}$ and the typical range of values for a steel equipment is around 0.05 – 0.15 $\mathrm{A/m^2}$. Comparing these values with the values obtained in the test, we can notice that the value is about 15% higher in the anode and 66% higher in the motor. But the reference values don't specify the exact composition of the environment nor the exact composition of the anode. The temperature or concentration of sodium chloride or other salts are indicated. There are different steel variations, neither the exact composition of the engine steel nor the composition of the reference values are indicated. Other possible reason is that in the tests done the surfaces were complex.

For higher engine speeds the values increase as the flow rate around the surfaces increases, as it can be observed in the (figure).

The corrosion rate calculated from the anode loss weight (94 nm/hr) for the thirty-one days test was four times lower than the calculated with the Faraday's law (398 nm/hr). The possible reasons are that Zinc oxides present in the surface of the anode were increasing the total mass, the composition of the anode might not be 100% pure Zinc and the duration of the test may cause corrosion rates variations.

Figure 5: 3D scan image of the anode after the test

The last test demonstrated the behaviour of the variation on the area ratio between the engine and the anode. The values of potential for the area variations are shown in the (table 7). and the expected behaviour for the potential is shown in the (figure 6), with the corresponding tendency line.

Table 7: Potential for different area ratios between anode and motor

Area Ratio Percentage $\frac{A_{anode}}{A_{cathode}} \times 100$	Anode Exp Area (mm^2)	Motor/Calomel electrode Potential (mV)
0,00	0	-727
0,23	3468,48	-802
0,98	14468,48	-937
1,15	16968,48	-954
1,45	21468,48	-980

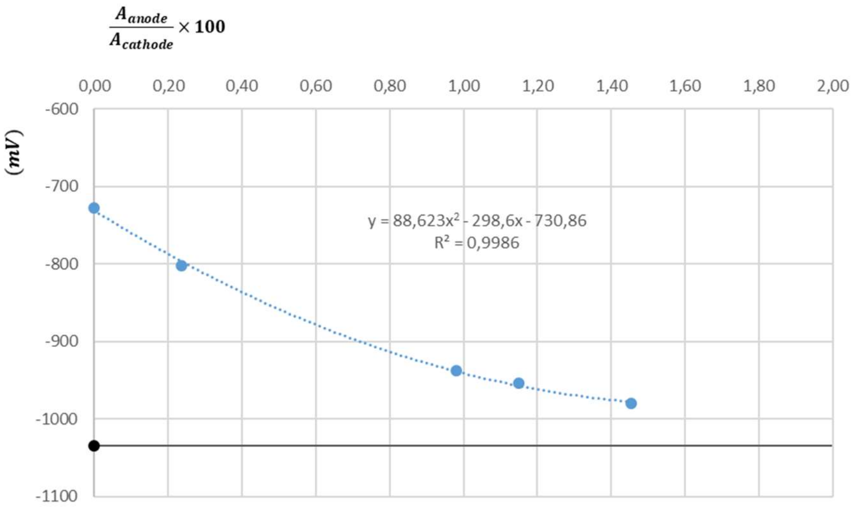

Figure 6: Potential tendency for different area ratios between anode and motor

With the tendency line, is possible to calculate the area in which the motor is not protected against the corrosion, following the manufacture guideline that state the motor should be maintained with a potential between -781 mV and -981 mV. Calculating the limit value of effective cathodic protection, we reach to an area ratio of 0.0018 that corresponds to an anode surface area of 2657.27 mm^2.

5. Conclusion

In this research, the RAM analysis principals were applied. The availability and reliability of some components were calculated. A Failure modes, effects and criticality analysis was performed to the outboard engine in order to identify and prioritize the failures that are encountered by the mechanics in the workshops. Counter-measures are proposed in this article, so that reliability and availability are increased. Since the Corrosion is a negative process frequently seen in the maritime motors, there were done three tests in order to understand better this process and how is the corrosion influenced. The behaviour of the current variation flowing between the anode and the cathode is studied for different engine speeds. The anode corrosion rate and the potential behaviour for the anode and engine area ratio variation was calculated.

6. References

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Table 8: Table of the analysis of total failure modes

Critical Function	Component	Detection	Failure Mode	Possible Cause	Possible Consequence	Corrective Action
Ensure power transmission to propeller	Gears	• No propeller action • Noise coming from lower unit	• No contact between gears	• Teeth dimensioning error (Insufficient resistance section) • Bad utilization	• Catastrophic lower unit failure causing adjacent component failures • No response to gear actions	• Gear change project • Educate users of misuse
Ensure fuel supply to injectors	Fuel pump	• Difficult start-up • Response failure • Non-motor operation • Circuit leakage	• Low Pressure	• Faulty Pressure Regulator	• Engine stop • Difficulty in achieving certain rotation regimes	• Pump Replacement • Inspection of the fuel circuit • Fuel analysis, both in terms of presence or water and debris
			• High Pressure	• Fuel circuit blocked		
			• Electrical Failure	• Faulty drive relay		
			• Mechanical Failure	• Worn impeller		
	Injectors	• Ignition Failure • Inconstant idling • Unstable power • High consumption • Use diagnostic system	• Inefficient fuel supply	• Contaminated fuel • Injectors with debris • Leaking injectors • Injectors permanently Closed/Open due to electrical problem • Dirtiness	• Ignition failure • Inconstant idling • Unstable power • High consumption	• Cleaning or replacing nozzles • Fuel analysis, both in terms of presence of water and debris • Development of more efficient filters/fuel filter systems
	Vapor Separator	• Response failure • Leakage	• Impossibility to maintain recommended pressure • Insufficient fuel cooling	• Damaged gasket • Clogging • Float blocked • Damaged cooling strip	• Response failed	• Replacement of the gasket • Replacing the throttle • Checking/replacing the cooling strip