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Reliability of a Light High Speed Marine Diesel Engine

Original scientific paper

The empirical reliability functions $R_e(t)$, failure rate $\lambda_e(t)$ and the density of failures $f_e(t)$ of the main marine diesel engine were determined using the empirical data on failures. It was found that the Weibull [1] distribution with parameters β=2.613 and η=400 approximated well the reliability of a light high speed marine diesel engine. Serial reliability configuration of the marine diesel engine subsystem was analysed and the failure frequency as well as the values of the failure rate by subsystems were determined. The further study will also determine the intervals for preventive replacement of the subsystem parts based on the empirical data which will be compared to the recommendations given by the manufacturer of marine diesel engines.

Keywords: *reliability, failure rate, marine engine*

Pouzdanost brzokretnog brodskog dizelskog motora lake konstrukcije

Izvorni znanstveni rad

Na temelju empirijskih podataka o otkazivanjima rada određene su empirijske funkcije pouzdanosti $R_e(t)$, intenziteta otkazivanja $\lambda_e(t)$ i gustoće otkazivanja $f_e(t)$ glavnog brodskog dizelskog motora. Utvrđeno je da Weibullova distribucija sa parametrima β=2,613 i η=400 dobro aproksimira pouzdanost brzokretnog brodskog dizelskog motora lake konstrukcije. Analizirana je serijska konfiguracija pouzdanosti podsustava brodskog dizelskog motora, te je utvrđena učestalost otkazivanjima kao i vrijednosti intenziteta otkazivanja po podsustavima. U nastavku istraživanja, a na temelju empirijskih podataka, utvrdit će se intervali preventivne zamjene dijelova podsustava, i isti usporediti s preporukama proizvođača brodskih dizelskog motora.

Ključne riječi: *pouzdanost, intenzitet otkaza, brodski motor*

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1 Introduction

For the Croatian Navy (HRM) it is very important to have reliable marine engine systems of multiple uses, such as marine diesel engines. The Croatian Navy naval vessels are equipped with light high speed diesel engines whose strength ranges from 1000-6000 kW. These motors are mostly made in "V" or "star-shaped structure", and the Croatian Navy missile boats are powered by engines of the world's two major manufacturers: *MTU* (*Motoren und Turbinen Union,* Friedrichshafen) and *ZVEZDA*, Saint – Petersburg [2]. Operational requirements of modern marine propulsion systems on naval vessels require that marine engines should be, on one hand, as easy and economical as possible with the ability to develop high power, and on the other reliable. These operational requirements include: maximal safety and durability, minimal weight and volume with greatest possible strength, maximum range, greatest possible manoeuvre including high readiness to set off, flexibility of machinery and optimal efficiency under small load, damage resistance and minimum possible contamination in operation at sea and minimum possible sounds and vibrations.

The fundamental requirement of the reliability of marine engines refers to the number of hours of engine failure-free performance. A light high speed marine diesel engine type M 503 A2 is required to work for 600 hours prior to the major overhaul [3]. Data from the Engine Log Book kept on board were used to determine the reliability of diesel engines. The ship's service regulations book stipulates keeping diary for all works and all engine starts. Every failure of the engine is kept in the ship's log, and especially in the log book of engine failures [4]. Failure of the engine means presence of conditions causing the engine out of order according to regulatory parameters. Failures can be divided into the failures which cause the engine breakdown, those which reduce the engine strength and those which do not reduce the engine strength but can be the cause of the engine breakdown. Analyzing empirical data on failures of the marine engine derived from the engine log book, and calculating the reliability function and failure rate function of marine engines it is possible to predict the expected failure-free operating hours and plan the process of preventive maintenance.

2 Reliability of marine diesel engine M 503 A2

The reliability of a technical system [5] is generally described by the reliability function R(*t*) given by the equation (1):

$$R(t)=\frac{f(t)}{\lambda(t)} \tag{1}$$

where:
$f(t)$ – failure density function
$\lambda(t)$– failure rate function.

According to the equation (1) it can be concluded that, for example, two different technical systems can have the same reliability $R_1(t)=R_2(t)$ at a given point of time t, but their failure rate $\lambda_1(t)$ and $\lambda_2(t)$ up to that time t can be different because the relation described by equation (2) is valid:

$$R(t)=\frac{f(t)}{\lambda(t)}=\frac{f_1(t)}{\lambda_1(t)}=\frac{f_2(t)}{\lambda_2(t)} \qquad (2)$$

Therefore, the reliability of a technical system is determined if two functions are known: reliability function $R(t)$ and failure rate function $\lambda(t)$. For a specific technical system, the reliability function and failure rate function are *unique*, i.e. specific failure rate function corresponds with specific reliability function. Most generally, the reliability function $R(t)$ can be mathematically described by equation (3) and can be applied to any failure density function $f(t)$.

$$R(t)=e^{-\int_0^t \lambda(t)dt} \qquad (3)$$

In that case the expected time of failure-free performance is determined by expression (4):

$$E(t)=\int_0^\infty R(t)dt \qquad (4)$$

where:
t- randomly changeable variable

Failure probability $P(T \le t)$ in the function of the time is given by equation (5):

$$P(T\le t)=F(t)=1-R(t) \qquad (5)$$

where:
$F(t)$ – system failure function

Then it is valid that the failure density function $f(t)$ equals the first derivative of the failure function $F(t)$, as described by equation (6):

$$f(t)=\frac{dF(t)}{dt} \qquad (6)$$

In the probability theory the function $f(t)$ is also called the failure density distribution function, while in the reliability theory failure density functions are applied for continuous processes as illustrated in Table 1.

The best and "most suitable" failure density function $f(t)$, and thus the failure rate function $\lambda(t)$, as well as the reliability function $R(t)$ are determined based on experimentally obtained data. In that context, it is defined by equation (7) i.e. the empirical failure density function $f_e(t)$:

$$f_e(t)=\lambda_e(t)\times R_e(t) \qquad (7)$$

Table 1 **Most common failure density distribution functions [6]**
Tablica 1 **Najčešće funkcije distribucije gustoće otkazivanja [6]**

Type of failure distri-bution	$f(t)$	$E(T)$
Expo-nential	$f(t)=\lambda\cdot e^{-\lambda\cdot t}$	$E(T)=\frac{1}{\lambda}$
Normal (Gauss)	$f(t)=\frac{1}{\sigma\sqrt{2\pi}}\cdot e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2}$	$E(T)=\mu$
Lognor-mal	$f(t)=\frac{1}{\sigma\cdot t\sqrt{2\pi}}\cdot e^{-\frac{1}{2}\left(\frac{\ln t-\mu}{\sigma}\right)^2}$	$E(T)=e^{\mu+\frac{1}{2}\sigma^2}$
Weibull	$f(t)=\frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}e^{-\left(\frac{t-\gamma}{\eta}\right)^\beta}$	$E(T)=\gamma+\eta\Gamma\left(\frac{1}{\beta}+1\right)$
Gama	$f(t)=\frac{1}{\eta\Gamma(\beta)}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}e^{-\frac{t-\gamma}{\eta}}$	$E(T)=\gamma+\eta\beta$

where:
$\lambda_e(t)$ – empirical failure rate function
$R_e(t)$ – empirical reliability function

Data on failures are obtained on the ground of the data on the use of the technical system. In this particular case, the data on failures of a marine diesel engine M 503 A2 are taken from the Engine Log Book [4]. Data on failures are shown in Table 2. Planned time of the engine operation time prior to major overhaul is t_p= 600 hrs.

Table 2 **Data on failures of marine diesel engine M 503 A-2**
Tablica 2 **Podaci o otkazivanjima brodskog dizelskog motora M 530 A-2**

Ordinal number of engine (*i*)	**Time of failure (t_i)**	**Ordinal number of engine**	**Time of failure (t_i)**	**Ordinal number of engine**	**Time of failure (t_i)**
1	89.5	14	250	27	461
2	102	15	285	28	490
3	120.5	16	304.4	29	490.3
4	124	17	320	30	495
5	150.3	18	322	31	495
6	180	19	327	32	495
7	202	20	330	33	558.15
8	220	21	350	34	571
9	220	22	380	35	577
10	223	23	380.3	36	580
11	228	24	395	37	580
12	236	25	430.3	38	585
13	237	26	450.3	39	590

If a technical system (in this case marine diesel engine) is renewed by maintenance or repairs, i.e. in case of so-called repairable systems, the expected time of failure-free work E(T), known as the Mean Time Between Failures (*MTBF*) is calculated by equation (8):

$$MTBF = \frac{1}{n}\sum_{i=1}^{n} t_i \tag{8}$$

where:
n – number of technical systems
t_i – the i[th] time of failure of the technical system

In case of the marine diesel engine M 503 A2 where n_{bds}=39 and according to Table 2, the Mean Time Between Failures is

$MTBF_{bds}$ = 13823.75/39 = 354 h

Operational availability of a technical system is the probability that the system, when used under specified conditions, will function satisfactorily at any point in time, whereas the observed time comprises the usage time t_k and non-usage time t_z. The operational availability is determined by equation (9):

$$O_r = \frac{t_k}{(t_k + t_z)} \tag{9}$$

The operational availability of the observed marine diesel engine is:

O_{rbds} = 13823.75/(13823.75+9576.25)=13823.74/23400=0.59

The same result for the operational availability is obtained if the Mean Time Between Failures (*MTBF*) is divided by the expected time of engine work prior to the major overhaul.

2 Determination of empirical failure density functions, failure rate and reliability

If n technical systems are used starting from t=0 to t_p=600 h, then at any point in time *t* will be $n_1(t)$ of the technical systems which did not fail. In that case the empirical failure density function $f_e(t)$ will be determined by equation (10):

$$f_e(t) = \frac{n_1(t_j) - n_1(t_j + \Delta t_j)}{n \Delta t_j} \tag{10}$$

where:

$$t_j \le t \le t_j + \Delta t_j$$

The empirical failure density function $f_e(t)$ equals the relation between the number of failures in the time interval Δt_j and the total number of systems n, previously multiplied by the length of the time interval Δt_j.

The empirical failure rate function $\lambda_e(t)$ will equal the relation between the number of failures in the time interval Δt_j and the number of systems which did not fail at the end of the time interval $n_1(t_j+\Delta t_j)$ previously multiplied by the length of the time interval Δt_j as determined by expression (11):

$$\lambda_e(t) = \frac{n_1(t_j) - n_1(t_j + \Delta t_j)}{n_1(t_j)\Delta t_j} \tag{11}$$

where:

$$t_j \le t \le t_j + \Delta t_j$$

The empirical reliability function $R_e(t_j)$ will equal the relation between the number of systems which did not fail at the end of the time interval $n_1(t_j+\Delta t_j)$ and the total number of systems *n,* i.e. equation (12) is valid:

$$R_e(t) = \frac{n_1(t_j + \Delta t_j)}{n} \tag{12}$$

where:

$$t_j \le t \le t_j + \Delta t_j$$

Based on equation (7), the following equation can expressed:

$$\left(\frac{n_1(t_j) - n_1(t_j + \Delta t_j)}{n\Delta t_j}\right) = \left(\frac{n_1(t_j) - n_1(t_j + \Delta t_j)}{n_1(t_j)\Delta t_j}\right) \times \left(\frac{n_1(t_j + \Delta t_j)}{n}\right) \tag{13}$$

$$f_e(t) = \lambda_e(t) \times R_e(t)$$

When the time intervals Δt_j are equal, their optimal number *k* can be determined by equation (14), [6]:

$$k = 1 + 3.3 \times \log n_2 \tag{14}$$

where:

n_2 – total number of failures.

For the total number of failures n_2=39 the optimal number of time intervals k_{bds} is:

k_{bds}= 1+3.3 × log39 = 6.25 (rounded down to the first whole number 6).

Accordingly, the time interval Δt_j^{bds} is:

$\Delta t_j^{bds} = t_p/6$ = 600/6 = 100 h.

Based on the data from Table 1 and in accordance with equation (13) the following relations are obtained and shown in Table 3.

Table 3 **Computational data**
Tablica 3 **Računski podaci**

Δt_j^{bds} [h]	$n_1(t_j)$- $n_1(t_j + \Delta t_j^{bds})$	$f_e(t)$[10^{-4}]	$\lambda_e(t)$ [10^{-4} fail./h]	$R_e(t)$
0 -100	1	1/(39·100)	1/(38·100)	38/39
100 - 200	5	5/(39·100)	5/(33·100)	33/39
200 - 300	9	9/(39·100)	9/(24·100)	24/39
300 - 400	9	9/(39·100)	9/(15·100)	15/39
400 - 500	8	8/(39·100)	8/(7·100)	7/39
500 – 600	7	7/(39·100)	7/(0·100)	0/39

The calculated values are shown in Table 4.

Table 4 **Calculated values of empirical functions**
Tablica 4 **Izračunate vrijednosti empirijskih funkcija**

Δt_j^{bds} [h]	$n_1(t_j)$- $n_1(t_j + \Delta t_j^{bds})$	$f_e(t)[10^{-4}]$	$\lambda_e(t)$ [10^{-4} fail./h]	$R_e(t)$
0 -100	1	2.56	2.63	0.974
100 - 200	5	12.8	15.15	0.846
200 - 300	9	23.07	37.5	0.615
300 - 400	9	23.07	60	0.384
400 - 500	8	20.45	114.28	0.179
500 – 600	7	17.94	-	0

The graphs in Figures 1, 2 and 3 show empirical functions of failure density, failure rate and failure reliability.

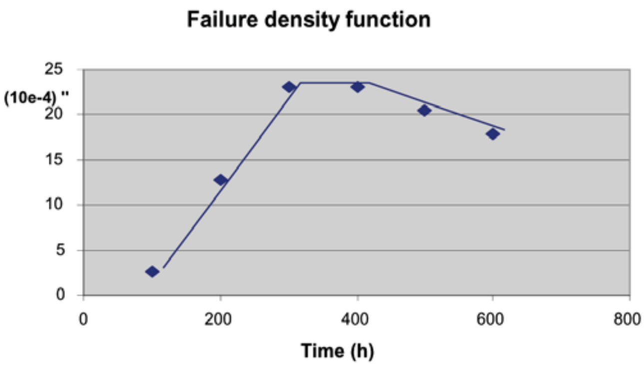


Figure 1 **Failure density function $f_e(t)$**
Slika 1 **Funkcija gustoće otkazivanja $f_e(t)$**

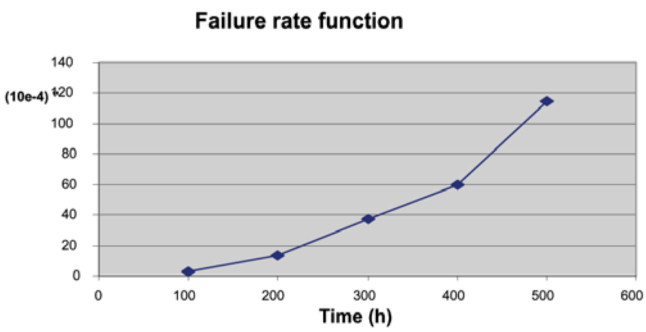
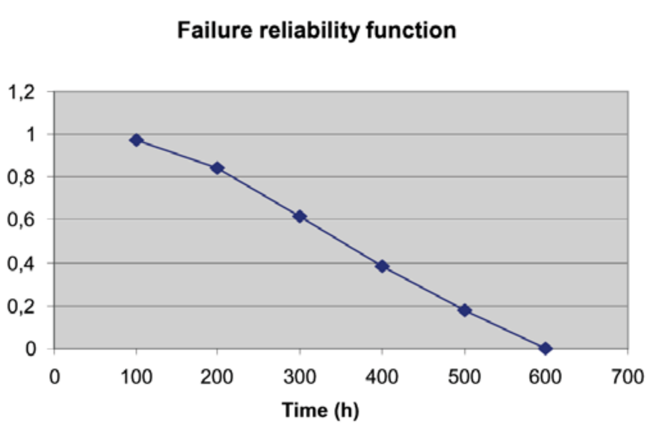


Figure 2 **Failure rate function $R_e(t)$**
Slika 2 **Funkcija intenziteta otkazivanja $R_e(t)$**

Figure 3 **Failure reliability function $R_e(t)$**
Slika 3 **Funkcija pouzdanosti $R_e(t)$**



A certain number of technical systems, as in this case the marine diesel engine, show a growing tendency of failure rate over time. The Weibull distribution enables the analysis of such forms of system failures.

3 Empirical functions approximation by the Weibull distribution

Assuming that the density failure function f(t) has the Weibull distribution, then the hypothesis H_0 is:

$$H_0: R(t)=R_v(t) \tag{15.1}$$

The alternative hypothesis H_1 is:

$$H1: R(t) \neq R_v(t) \tag{15.2}$$

where [7]:

$$R_V(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{(see Table1)} \tag{16}$$

i.e.:
γ –location parameter, β –shape parameter i η –scale parameter

Methods used to determine distribution, in order to approximate empirical data, are categorized into two major groups: graphical and analytical. Graphical methods are easier and are more common in engineering practice, and are implemented in this research as well. A graphical method generally consists of drawing a graph (diagram) containing the empirically estimated data, and the data obtained on the basis of probability distribution, later used in approximation of the empirical data. In that case the Weibull distribution is supposed to be a good model for the data given in Table 3. If the plotted dots can be easily approximated by a straight line, then the assumed model is appropriate. Otherwise, the model is inappropriate. Using the procedure described above, it is possible to evaluate the validity of the model and of the distribution parameters. The first step is to estimate parameter γ based on median rank for the given sample size [6]. If the sample size is large enough, the size of the median rank is estimated pursuant to expression (16.1):

$$MR_i \approx i/(n+1) \tag{16.1}$$

where
i – is the failure order number, and n – is the total sample size.

After the median rank has been estimated, function $g\,(t_i, MR_i)$ is linearised, and if it can be approximated by a straight line, then γ=0. Figure 4.1 shows the graph of the function $g(t_i, MR_i)$.

Since the function $g\,(t_i, MR_i)$ can be approximated by a straight line, then the reliability function $R_v(t)$ assumes the following configuration:

$$R_V(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{17}$$

i.e. failure rate function is:

$$\lambda_V(t) = \frac{\beta}{\eta} \times \left(\frac{t}{\eta}\right)^{\beta-1} \tag{18}$$

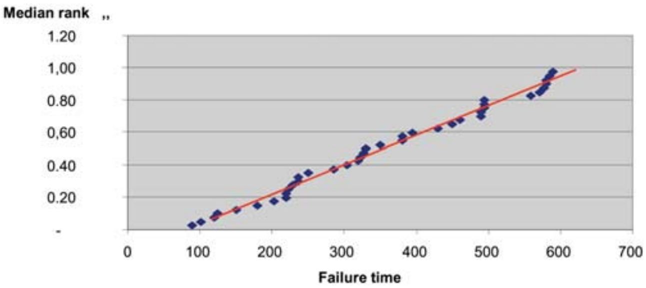


Figure 4.1 **Median rank**
Slika 4.1 **Medijalni radijan**

where: $\beta>0$ and $\eta>0$ are parameters.

The above mentioned reliability function (17) is not mathematically appropriate for the approximation of the experimental results and for the estimation of parameters $\beta>0$ and $\eta>0$.

Therefore, when applying the mathematical operation of logarithm (natural logarithm ln), the reliability function may also be written as [7]:

$$y = \beta \times x + c \qquad (19)$$

where:

$$y = \ln[-\ln R_v(t)] \qquad (19.1)$$

$$x = \ln t \qquad (19.2)$$

$$c = -\beta \times \ln\eta \qquad (19.3)$$

On the basis of the experimental results shown in Table 4, it is necessary to determine $y_j=y(t_j)$ and $x_j=x(t_j)$ as shown in Table 5.

Table 5 **Rates y and x**
Tablica 5 **Vrijednosti y i x**

t_j	x_j	y_j
100	-3.636	4.6
200	-1.788	5.29
300	-0.721	5.7
400	-0.043	5.99
500	0.572	6.21

NB. The rate of point t=600 is not taken into account because R(t)=0

Since equation (19) is the mathematical description for the straight line function, parameter β is actually the coefficient of the straight line which can be calculated on the basis of expression (20), and parameter c on the basis of expression (19) when $\beta = \hat{\beta}$ is known, i.e. the equation is (21):

$$\hat{\beta} \approx \Delta y_j / \Delta x_j \qquad (20)$$

$$\hat{c} \approx y_j - \hat{\beta} \times x_j \qquad (21)$$

Using the results from Table 5, $\hat{\beta}$ and $\hat{c}$ values are calculated as follows:

$\hat{\beta} = (-3.636-0.572)/(4.6-6.21) = -4.208/-1.61 = 2.613 \times$
$\times(-3.636-0.572)/(4.6-6.21) = -4.208/-1.61 = 2.613$
$\hat{c} = -3.636-2.613 \times 4.6 = -15.655$

Pursuant to (20) and (21), the straight line equation approximating from (19), is (22):

$$y = \hat{\beta} \times x + \hat{c} \qquad (22)$$

Figure 4.2 shows the values from Table 5 in the form of graph. Table 6 shows the values from Table 5 that are estimated using equation (22), while Figure 4.3 compares the empirically obtained data and those obtained on the basis of the Weibull probability distribution.

Table 6 **Empirical and calculated data**
Tablica 6 **Empirijski i izračunati podaci**

x_j	y_j	$y_j = y_j(\hat{\beta}, \hat{c})$
4.6	-3.636	-3.635
5.29	-1.788	-1.83
5.7	-0.721	-0.76
5.99	-0.043	0.003
6.21	0.572	0.571

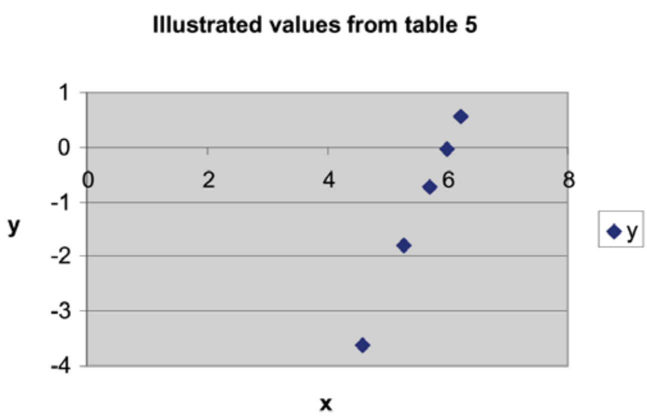
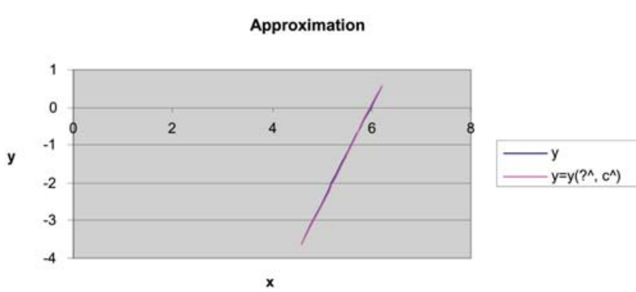


Figure 4.2 **Data from Table 5**
Slika 4.2 **Podaci iz tablice 5**

Figure 4.3 **Approximation of empirically obtained data by the Weibull distribution**
Slika 4.3 **Aproksimacija empirijski dobivenih podataka Weilbullovom distribucijom**



On the basis of approximated data $y=y\,(\hat{\beta}, \hat{c})$ and according to equation (19.3), it follows:

$$\eta = e^{-\frac{c}{\beta}} = \eta = e^{-\left(\frac{-15.655}{2.613}\right)} = e^{5.9912} = 399.98 = 400$$

From this derives that it is possible to write the marine diesel engine reliability function $R_r(t)$ when the density failure function follows the Weibull distribution:

$$R_V(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{t}{400}\right)^{2.613}} \qquad (23)$$

Figures 5 and 6 show the reliability and rate graphs obtained from the empirical data and approximation based on the Weibull distribution:

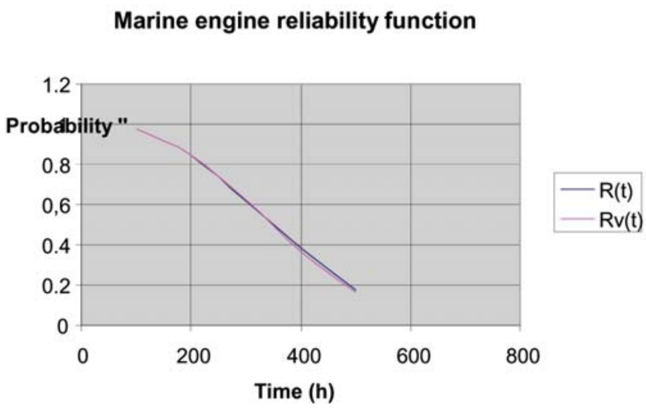


Figure 5 **Marine diesel engine reliability function $R_e(t)$ and $R_v(t)$**
Slika 5 **Funkcija pouzdanosti brodskog dizelskog motora $R_e(t)$ i $R_v(t)$**

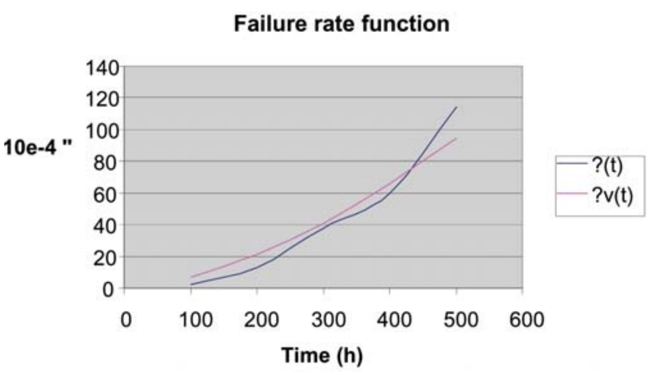


Figure 6 **Marine diesel engine failure rate function $\lambda_e(t)$ and $\lambda_v(t)$**
Slika 6 **Funkcija intenziteta otkazivanja brodskog dizelskog motora $\lambda_e(t)$ i $\lambda_v(t)$**

Pursuant to the expression for the calculation of the expected time of failure given in Table 1 in case of the Weibull distribution, E(*T*) equals:

$$E(T) = \gamma + \eta \times \Gamma\left(\frac{1}{\beta} + 1\right) = 0 + 400 \times \Gamma\left(\frac{1}{2.613} + 1\right) =$$
$$= 400 \times \Gamma(1.38) = 400 \times 0.87 = 348\text{h}$$

According to equation (18) the failure rate for the expected time of failure E(T) is:

$$\lambda_V(t) = \frac{\beta}{\eta} \times \left(\frac{t}{\eta}\right)^{\beta-1} = \frac{2.613}{400} \times \left(\frac{348}{400}\right)^{1.613} = 52.18 \times 10^{-4} \text{ failure/ h}$$

According to the empirical data from Table 4 the value of failure rate $\lambda_e(350)$ can approximately be calculated with linear interpolation as follows:

$$\lambda_{esr}(350) \approx [\lambda_e(300) - \lambda_e(350)]/2 = (37.5\cdot 10^{-4} - 60 \times 10^{-4})/2 =$$
$$= 48.75 \times 10^{-4} \text{ failure//h}$$

It is also possible to calculate $R_v(348)$, $R_{esr}(350)$, $f_v(348)$ and $f_{esr}(350)$.

$$R_V(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{348}{400}\right)^{2.613}} = 0.5$$

$$R_{esr}(350) \approx [R_e(300) - R_e(350)]/2 = (0.615-0.384)/2 = 0.517$$

i.e.

$$f_v(T) = \lambda_v(T) \times R_v(T) = 52.18 \times 10^{-4} \times 0.5 = 26.09 \times 10^{-4}$$
$$(350) = \lambda_{esr}(350) \times R_{vsr}(350) = 48.75 \times 10^{-4} \times 0.517 = 27.78 \times 10^{-4}$$

Table 6 illustrates the empirical data in relation to those obtained on the basis of the hypothesis (Hypothesis H_0) on the-Weibull distribution, and the difference between empirical and calculated data is determined.

Table 7 **Comparison of empirical data and those obtained by the Weibull distribution**
Tablica 7 **Usporedba empirijski dobivenih podataka i izračunatih temeljem Weilbullove distribucije**

Data	Time of failure	Reliability *R*(*t*)	Failure rate $\lambda(t)$	Failure density *f*(*t*)
Empirical	$MTBF_{bds}$= = 354 h	$R_{esr}(350) \approx$ ≈ 0.517	$\lambda_{esr}(350) \approx$ ≈ $48.75\cdot 10^{-4}$	$f_{esr}(350) \approx$ ≈ $27.78\cdot 10^{-4}$
Weibull distribution	E(*T*)=348 h	$R_v(T)$=0.5	$\lambda_v(T)=52.18\cdot 10^{-4}$	$f_v(T)=26.09\cdot 10^{-4}$
Difference	6 h (1.7%)	0.017 (3.2%)	3.43·10e-4 (7%)	$1.69\cdot 10^{-4}$ (6%)

Following the data shown in Table 7 it is accepted that reliability function hypothesis H_0 for the marine diesel engine type M 503 A2 has the Weibull distribution. It is not possible to accept the hypothesis of constant failure rate value, i.e. that the failure rate is not time dependent. In case of constant failure rate, equation (24) is valid:

$$\lambda = \frac{1}{\text{MTBF}_{bds}} = \frac{1}{354} = 28.24 \times 10^{-4} \text{ failure/h} \qquad (24)$$

The obtained failure rate value is significantly lower than the empirical one and the one calculated on the basis of the Weibull distribution. In the process of estimating certain technical system reliability it is common to assume that the failure rate is constant.

In that case so-called random failures are present and the failure rate is not time dependent. It is also known that the failure rate with most of electrical systems is constant, i.e. not time dependent. Reliability analysis of the marine diesel engine type M 503 A2 shows continuously rising failure rate function and the fact that the reliability of the above mentioned marine diesel engine can be well approximated by the Weibull distribution. Despite its complexity, the Weibull distribution is commonly used when estimating reliability. It includes decreasing, constant, and increasing failure rate functions.

The reasons for the marine diesel engine failure vary from overloaded engine and fatigue of materials to wear and corrosion. It is necessary to determine the failure rates of the technical system parts and determine their contributions to the reliability and failure rate of the marine diesel engine, as follows.

4 Marine diesel engine subsystem failure rate

Every technical system whose reliable operating depends on each of the subsystems within the system represents a model of serial reliability configuration. Figure 7 shows a block diagram of a marine diesel engine defined with 9 subsystems whose names are given in the caption of Figure 7 [8].

Marine Diesel Engine M 503 A2, produced by *ZVEZDA*, Saint-Petersburg is a high-speed, multicylindrical, star derived, water-cooled four-stroke engine, supercharged with turbocharger. The engine has 42 cylinders in seven blocks placed star. Each block has six cylinders. The angle between the engine block is 51° 25‘43”. A cylinder block with the cylinder head is cast from aluminum alloy. Maximum engine power while running forward, (the number of engine crankshaft revolutions of 36.67 s with the following atmospheric conditions: air temperature at the inlet 20° C, atmospheric pressure 1013 bar, 70% relative humidity, fuel temperature and seawater at entrance 20 °C) is 2944 kW. Exploitation engine power when running forward and when the number of crankshaft revolutions is 31.67 s is 2429 kW. The RPM of the output shaft of the coupling when running forward and at maximum power is limited to 17.16 10^{-1} sec. The RPM of the output shaft while running aft is 8.58 10^{-1} sec. The mass of the diesel engines (dry) with a buckle and gearbox and all the auxiliary aggregates is 7150 kg [3] and [2].

If T_{ri} is a randomly changeable variable representing the period of time by the moment of failure of r^{th} subsystem, then the reliability of a technical system, composed of *m* serially connected subsystems in one whole, on the basis of equation (5), is defined by expression (25):

$$R(t) = P(T_1>t \cap T_2>t \cap \cdots \cap T_r>t \cap \cdots \cap T_m>t) \qquad (25)$$

Assuming that subsystem failures are independent from one another, relation (25) will take the following form:

$$R(t) = P(T_1>t)P(T_2>t)\cdots P(T_r>t)\ )\cdots P(T_m>t) \qquad (26)$$

Thus it equals [9]:

$$R(t) = \prod R_r(t),\ r=1,2,3 \cdots m \qquad (27)$$

where:
$R_r(t)$ – is the reliability of the r^{th} subsystem.

On the basis of equations (39) and (27) it follows that:

$$\lambda(t) = -\frac{d\left[\ln R(t)\right]}{dt} = -\frac{d\left[\ln \prod R_r(t)\right]}{dt} = -\sum \frac{d\left[\ln R_r(t)\right]}{dt} = \sum_{r=1}^{m} \lambda_r(t) \qquad (28)$$

Thus: $\lambda(t) = \sum_{r=1}^{m} \lambda_r(t)$, $r=1,2,3 \cdots$ m.

Therefore, the failure rate function of the technical system $\lambda(t)$ equals the sum of the failure rate functions of individual subsystems λ_r(t) which compose the system regardless of the density failure function of an individual subsystem λ_r(t), on the assumption of independence of failures of subsystems. Table 8 shows failures per particular subsystems.

Table 8 **Failures per subsystems**
Tablica 8 **Prikaz otkazivanja po podsustavima**

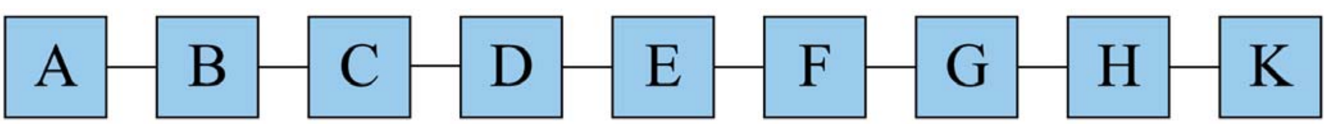
t_i	A	B	C	D	E	F	G	H	K
100	0	0	1	0	0	0	0	0	0
200	1	1	2	1	0	0	0	0	0
300	1	1	5	1	0	1	0	0	0
400	0	1	3	4	0	1	0	0	0
500	1	1	2	0	3	1	0	0	0
600	0	3	0	1	0	0	1	1	1
∑=39	**3**	**7**	**13**	**7**	**3**	**3**	**1**	**1**	**1**

Figure 8 shows the sequence of frequency of number of failures per subsystems.

Further analysis of the data from Figure 8 indicates the following:

a) Coupling – 13 failures appeared due to the cone synchroniser of the coupling (3), radial axial bearing (2), claw coupling, actuating lever (2), gear lever bearing (3), coupling casing (1) and gear box mechanism for reverse sailing

Figure 7 **Block diagram of the marine diesel engine of serial reliability configuration**
Slika 7 **Blok dijagram brodskog dizelskog motora serijske konfiguracije pouzdanosti**



Key:
A – turbine
B – turbocompressor
C – coupling
D – block cylinder
E – pistons
F – main connecting rod
G – sliding bearing
H – gudgeon pin
K – outlet valve

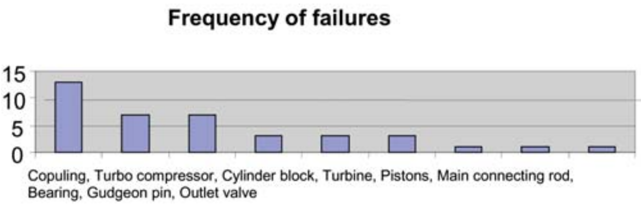


Figure 8 **Frequency of failures**
Slika 8 **Učestalost otkazivanja**

b) Turbo compressor – 7 failures appeared due to the wrist pin (2), oil pipe (1), seal (1) and associated apparatus (3)
c) Turbine – 3 failures appeared due to the bearing ring (1), seal (1) roller bearing (1)
d) Pistons – 3 failures appeared due to the gudgeon pin (1) and piston ring (2)
e) Main connecting rod – 3 failures appeared due to the ring lock (1) and roller lock (2).

These data provide guidelines in term of conducting corrective maintenance activities.

Failure rate values are shown in Table 9.

Table 9 **Failure rate values per subsystems [10^{-4}]**
Tablica 9 **Vrijednosti intenziteta otkazivanja po podsustavima [10^{-4}]**

t_j	λ_A	λ_B	λ_C	λ_D	λ_E	λ_F
100	0	0	2.63	0	0	0
200	3.03	3.03	6.06	3.03	0	0
300	4.16	4.16	20.83	4.16	0	4.16
400	0	6.66	20	26.66	0	6.66
500	14.28	14.28	28.57	0	42.85	14.28

Remark: Value in point t=600 is not taken into consideration because *R*(*t*)=0.
Napomena: Vrijednost u točci t=600 nije uzeta u obzir jer je *R*(*t*)=0.

Figure 9 shows failure rate functions per individual subsystem and total failure rate function for the technical system.

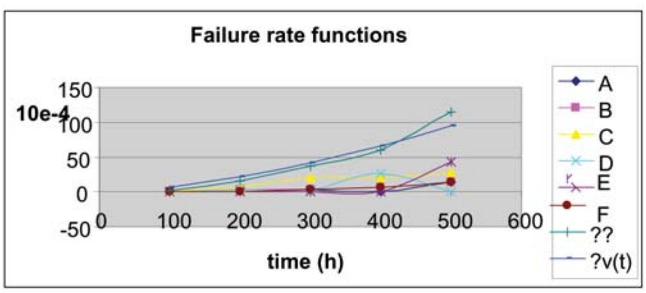


Figure 9 **Rate functions per individual subsystem and total failure rate function**
Slika 9 **Funkcije intenziteta otkazivanja po podsustavima i ukupna funkcija intenziteta otkazivanja**

Table 10 shows the times of failures of individual subsystems of the marine diesel engine.

The carried out analysis of the marine diesel engine subsystems and individual components of the subsystem that caused the failure shows an important characteristic of so-called mechanical parts (unlike so-called electrical parts) and that is - the mechanical parts cannot fail by the law of exponential distribution with a constant failure rate, but they show constant increasing failure in the function of technical system operation time. This phenomenon is caused by a failure mode of mechanical parts, and it is manifested as the result of material fatigue, corrosion, creep of materials and similar processes that in the technical system operation time only increase the probability of causing a technical system failure. Therefore, for studying the reliability of marine diesel engines, it was necessary to determine the behaviour of so-called mechanical parts of the system which failed. For a technical system, such as marine diesel engine, functionally composed of such parts (elements), it is important to emphasize that it has a variable failure density function over its operation time in the

Table 10 **Times of failures of individual subsystems**
Tablica 10 **Vremena otkazivanja elemenata pojedinog podsustava**

	t_j	100	200	300	400	500	600
A-turbine $MTBF_A$ =302.43 h	bearing ring		180				
	seal			237			
	roller bearing					490.3	
B-turbo compressor $MTBF_B$ =424.63 h	wrist pin		150.3		327		
	oil pipe			285			
	seal					495	
	associated apparatus						558.15
	-”-						577
	-”-						580
C-coupling $MTBF_C$ =254.97 h	cone synchroniser			250	304.4		
	-”-				320		
	radial axial bearing			202			
	-”-			220			
	claw coupling	89.5					
	actuating lever		102				
	-”-		120.5				
	gear lever bearing				330	430.3	
	-”-					495	
	coupling casing			223			
	gear box mechanism			228			
D-cylinder block $MTBF_D$ =337.42 h			124	220	322		571
					350		
					380		
					395		
E-pistons $MTBF_E$ =472.65 h	gudgeon pin					450.3	
	ring					495	
F-main connecting rod $MTBF_F$ =391.83 h	ring lock			236		461	
	roller lock				380.3	490	
G – sliding bearing							590
H – gudgeon pin of attaching piston							585
K –outlet valve							580
	number of failures	1	5	9	9	8	7

course of which the parts (elements) get old, fail and are replaced with the new parts (elements). Therefore, it is also emphasized that the concept of "constant mean time between failures" may be applied in the technical systems with mainly mechanical parts, in which preventive maintenance is carried out, when the so-called state of *balance* is reached. The so-called *balance* is reached by applying exclusively preventive maintenance, in a way that parts of the technical system are preventively replaced before their failure rate starts to increase rapidly. Then it can be assumed that the technical system, in the considered case of the marine diesel engine, fails by the law of exponential distribution, whereas the failure rate has a constant level and is independent in relation to time. In that case, the failures occur randomly.

If each of l^{th} subsystem or element of a technical system is preventively replaced as soon as it accumulates T_{pl} ($l = 1,2 \cdots m$) hours of continuous operation, then average failure rate λ_l of the subsystem is determined by expression (29) [6]:

$$\lambda_l = \frac{\left[1 - R_l\left(T_{pl}\right)\right]}{\int R_l\left(t\right)dt}, \; 0 \le t \le T_{pl} \tag{29}$$

The mean time between the technical system failures in state of *balance* is determined by expression (30):

$$M_s = \frac{1}{\sum_{l=1}^{m} \lambda_l}, \; l = 1,2 \cdots m \tag{30}$$

In the follow-up research on the reliability of the light marine diesel engine and its preventive maintenance, the attention will be focused on determining the failure rate in cases of preventive replacement of a subsystem or its parts, through two categories of replacement: replacement after certain operation time and block replacements.

5 Conclusion

The reliability of marine diesel engine is its capability to operate without failure during a specified period of time (i.e. time of use), and the maintainability is constructional characteristic specified by diesel engines capability as a technical system to maintain (through preventive maintenance) or return (through corrective maintenance) in the proper operational condition. Time is a major factor and measures the effectiveness of the technical system. Lower downtime increases operational readiness and availability of the system as a whole, so in terms of reliability and maintainability two capabilities are considered: a) capability of staying in operating condition by preventing failures due to aging, wear, corrosion and similar processes (preventive maintenance) and b) capability of rapid return to operational condition after random failures (corrective maintenance).

Preventive maintenance (i.e. preventive replacements of parts) is applied when the technical system and its subsystems (parts) have the increasing rate of failures in relation to the use of the system. Specifically, in the case of a constant rate of failure, preventive replacements would not affect the security of the achieved level of reliability, and maintenance costs would increase. In this case, when the failures are random, optimal procedure would be replacement of the parts in case of a failure. The conducted research regarding the reliability of the light marine diesel engine showed that one cannot take for granted the assumption about constant failure rate λ (t) = const. Therefore, empirical approximation of functions was taken and it showed that the Weibull distribution with parameters $\beta = 2.613$ and $\eta = 400$ approximates well the reliability of the light high-speed marine diesel engine M 503 A2, and that the expected time of failure-free function E (T) = 348 h. Starting from the established fact that marine diesel engine has an increasing rate of failure, and that failure causes may be different in nature: from overloading the engine and fatigue of material, to wear and corrosion, it was necessary to determine the individual failure rates of diesel engine subsystems (parts) and their contribution to overall reliability and failure rate.

It is well known that the mechanical parts of a technical system, unlike electrical parts, have immensely increasing failure intensity in the course of a technical system operation time. This is caused by failure mode of the mechanical parts, and it is manifested as a consequence of the material fatigue, corrosion, material creeps and similar processes which, with time of system operation, only augment the probability of causing the failure of the technical system. Thus, for studying the reliability of a marine diesel engine it was necessary to define the behaviour of so called mechanical parts of that system that have experienced failure, because only with the application of preventive maintenance in the way that the subsystems (parts) of the marine diesel engine are preventively replaced prior to the abrupt increase of the failure rate, the so called state of balance is achieved when it is possible to apply the concept "constant mean time between failures".

The task of preventive maintenance is to prevent the degradation of design characteristics of the marine diesel engine in the way that the planned activities are implemented in order to prolong the material life cycle and prevent the increase of failure rate. Because of that, it is of crucial importance in the continuation of research to define on the basis of empirical data the intervals of preventive part replacements and compare them to the recommendations of marine diesel engine manufacturers. It is a routine procedure that these intervals are to be defined in accordance with the previous experiences, and optimised depending on empirical data gathered during the exploitation of the technically complex systems such as marine diesel engines. The empirical data presented in this paper gathered from the marine diesel engine exploitation, which served to define the characteristics of individual subsystem operation and approximation of pertaining functions, are of great importance (together with data on preventive replacement costs) for defining optimal intervals of preventive replacement of individual subsystems (parts) of the main system (light high speed marine diesel engine for the propulsion of fast naval vessels).

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