Application of the Two-Parameter Weibull Distribution Method to Assess the Reliability of Mitsubishi S&U Marine Diesel Engine Crankshaft

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Abstract: In this study, the reliability of Mitsubishi S&U marine diesel engine crankshaft is analyzed using the two-parameter Weibull distribution method. The study involves the analysis of the failure times of Mitsubishi S&U marine diesel engine crankshaft. The mean time to failure (MTTF), failure rate and reliability were successfully computed using the values of the shape and scale parameters. The results of our analysis showed that the failure rate of the crankshaft in its early wear-out period is increasing steadily over time. The reliability of the crankshaft was found to be 84.696%. This result can be used to carry out timely and effective maintenance of the machineries, thus improve their operations and availabilities.

Keywords: Reliability, Crankshaft Failure, Weibull Distribution Method, Mean Time to Failure, Rank Regression.

Introduction

Internal combustion (IC) engines are used in various industries, including marine and offshore ones because of their reliability and efficiency. In marine and offshore industry, it is used for power generation or ship propulsion, therefore failure of the engine must be avoided. The IC engines are categories into two, such as spark ignition and compression ignition engine. Diesel fuel is introduced at a pressurized peak into the cylinder after the air has been compressed to such a point where auto-ignition occurs. In terms of efficiency, the compression ratio of diesel engines is twice that of spark ignition engines (Taylor, 2003).

Failure of marine diesel engine crankshaft onboard a vessel can result in downtime. Downtime is the stipulated period of time in which equipment is not able to perform to specification. This action of downtime may result in production loss and this loss is unsatisfactory to marine and offshore industry. According to Trbojevic and Soares (2000), hazardous industries have developed methodologies for dealing with safety and loss prevention, from the design standards to plant inspections, technical safety and human factors. According to Mokashi *et al*. (2002), maintenance constitutes a significant part of the overall performance and operating costs in marine operations. Recently, engineers are faced by the severe problem of crankshaft failure and most crankshaft fracture is due to fatigue failure. It is difficult to analyze fatigue phenomenon and presently it is extremely treated important as severe problems are encountered.

Fracture study of boxer engine crankshaft was investigated by Fonte and Freitas (2009). According to the authors, the caused for the catastrophic failure of crankshaft was poor design of steel support shells and bedplate bridges. Li *et al*. (2012) studied diesel engine crankshaft failure using Fractographic analysis. Observation from the study showed that fracture occurred in the zone between the 2nd crankpin and 2nd journal. Fractographic analysis indicated that fatigue is the cause of the crankshaft failure. The partial absence of the nitride layer may result from over-grinding after nitriding. Failure analysis was performed on two diesel engines crankshafts by Silva (2006). Both investigated crankshafts revealed damaged in short time after repair of the engine. The reason for early failure was caused by wrong grinding process.

Espadafor *et al.* (2009) investigated the catastrophic failure of V16 diesel engine crankshaft of a power plant for electrical generation which was running at 1500 rpm and failed after 20000hr of its continuous service operation on its maximum loading. Different approach was carried out to study the reason of failure and each of them concluded fatigue as a cause of failure. Low alloy steel was used to produce the crankshaft. To determine the chemical composition of the material, chemical analysis was performed on the specimen. The result revealed was satisfactory for the functioning of the crankshaft. Ronald (2005) investigated gas turbine component failure in using Weibull distribution methods to study failure in gas turbine component. Djeddi *et al*. (2015) utilized operational reliability to a gas turbine based on three parameter Weibull distribution. The study concentrated on the problems of reliability analysis in industrial equipment.

In this study, the two-parameter Weibull distribution is used to model the failure time of Mitsubishi S&U marine diesel engine crankshaft using the rank regression estimation method. The Windchill quality solutions 11 software was used to estimate the weibull parameters such as MTTF, failure rate and the reliability of the marine diesel engine.

Methodology

In this paper, Mitsubishi main engine crankshaft was used as a case study. Data containing failure times of the crankshaft during the operating period of 2010 to 2020 was obtained from maintenance records and logs. This data was analyzed and modeled using two-parameter Weibull distribution, facilitated by use of a reliability software. The rank regression estimation method is employed to obtain estimates of the Weibull distribution. In order to apply the rank regression estimation method, the failure times were ranked in order of increasing magnitude; from smallest to highest. There are many distributions that can be used to model failure data, such as the normal distribution, exponential distribution, Rayleigh distribution, Weibull distribution, Gamma distribution and others. The challenge of fitting distributions to reliability data is the ability to identify the category of distribution and parameters values that give the highest probability of obtaining the observed data. Probability density functions used in industry is the Weibull distribution. Weibull distribution can be applied to a large number of situations. It is also used to model both increasing and decreasing failure rates. Weibull analysis utilizes the weibull distribution in estimation of time to failure. The main advantage of using this distribution is its ability to handle small samples of failure data and its flexibility in fitting different failure modes. It also produces an easy-to-understand plot. Small samples are very common in reliability testing because tests are often destructive in nature and also very costly. Weibull can be fitted in two-parameter or three parameter distributions.

In this paper, the two-parameter distribution is chosen over the three parameters because its application is more common and very efficient when dealing with the small sample size. The scale parameter (η) and shape parameter (β) are the two parameter of Weibull distribution, while the location parameter is assumed to be zero. Shape parameter (β) value is utilized in determination of the shape of the distribution. Whenever $\beta < 1$, it implies the failure rate is decreasing, thus there is high probability of failing at early stages (infant mortality). If $\beta = 1$, it implies the failures are independent of time (constant failure rate). If $1 < \beta < 4$, it implies the failure rate is increasing.

This is also known as the early wear out period which can be due to generic failure modes such as improper grinding, misalignment, fatigue or high operating temperature. When $\beta > 4$, it means rapid wear out of the journal bearings, meaning steep curve with fast wear out at some point. In the past, techniques to perform Weibull analysis by hand were tedious and less accurate. These days, the process has been replaced by specialized Weibull analysis software programs that can accurately estimate the Weibull parameters and also automatically produce Weibull plots from a given data sets. In this study, TPC Windchill Quality Solutions 11.0 software package is used to determine the estimates of two-parameter Weibull distribution (β and ή). When the estimates of the two-parameter Weibull distribution are accurately obtained, they can be used to assess the MTTF and reliability of the marine diesel engine crankshaft.

The following equations below are used to determine the MTTF and reliability of two-parameter Weibull distribution.

$$\text{MTTF} = \boldsymbol{\eta}\,\Gamma\left(1 + \frac{1}{\beta}\right) \tag{1}$$

The failure rate function, which is also called the hazard rate is detailed below:

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{2}$$

The reliability function of the Weibull distribution is outlined as follows:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3}$$

Where t, $\beta\,\boldsymbol{\eta} > 0$

$$\Gamma(x) = \int_0^{\infty} e^{-x} x^{n-1} \tag{4}$$

Where Γ(x) = Gamma Function

$\boldsymbol{\eta}$= scale parameter

β = shape parameter

t = Time to failure

Weibull Parameters Estimation

There are several methods of estimating Weibull parameters, such as the maximum likelihood estimation, method of moment and median rank regression. Olteanu and Freeman (2010) studied the performance of maximum likelihood estimation (MLE) and median rank regression (MRR) methods and they concluded that the median rank regression method offered the best combination of accuracy and ease of interpretation, when the sample size and number of suspensions are small. This method is important because of its ability visualized fitting. The median rank regression method is therefore used in this study because it will offer the best fit for our small sample size.

In addition, this method provides a good measure of the goodness-of-fit of the selected distribution in the correlation coefficient. The rank regression method determines the way estimated unreliability's are associated with failure times under consideration. The median rank method failure order number and the cumulative binomial distribution. In the rank regression method, the Weibull shape and scale parameters (β and ή) are determined using the following equations:

$$\beta = \left[\frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2}\right] \tag{5}$$

$$\ln \boldsymbol{\eta} = \left[\frac{(\sum y) - \beta(\sum x)}{n}\right] \tag{6}$$

The rank regression method can provide a good measure for the fit of the line to the data points. This measure is known as the correlation coefficient, ρ. In life data analysis, it is a measure for the strength of the linear relation between the median ranks (y-axis values) and the failure time data (x-axis values). The median rank and failure time data are y and x axis values respectively. The correlation coefficient is expressed using the equation below:

$$\rho = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{7}$$

Where σ_{xy} is the covariance of x and y, σ_x is the standard deviation of x, and σ_y is the standard deviation of y. The closer the value of the correlation coefficient, ρ, is to the absolute value of 1, the better the linear fit. Note that when $\rho = +1$ indicates a perfect fit with a positive slope, while -1 indicates a perfect fit with a negative slope. A perfect fit means that all of the points fall exactly on a straight line. A correlation coefficient value of zero would indicate that the data points are randomly scattered and have no pattern or correlation in relation to the regression line model.

Results and Discussion

Results

The failure times of the marine diesel engine crankshaft is shown in Table 1. In order to apply the rank regression method, the data in Table 1 were arranged in increasing order of magnitude (from smallest to largest). The smallest value (811) is assigned the rank of 1, followed by the second smallest value (813) and so forth to the highest value (2854) ranked 15. These ranked data is presented in Table 2.

Table 1. Raw data of failure time (hours) of the marine diesel engine crankshaft

1045
1214
1298
811
1407
813
1450
2361
1655
2623
2574
2530
2361
2048
2854

Table 2. Ranked Failure time of the crankshaft

Rank	Failure time (hour)
1	**811**
2	**813**
3	**1045**
4	**1214**
5	**1298**
6	**1407**
7	**1450**
8	**1655**
9	**1807**
10	**2048**
11	**2361**
12	**2530**
13	**2574**
14	**2623**
15	**2854**

The MTTF, failure rate λ(t) and reliability of the crankshaft can be obtained by applying the results obtained in our analysis. Where:

$\boldsymbol{\beta}$ = 2.8065, $\boldsymbol{\eta}$ = 1977.5312, $\rho = 0.9763$, $\rho^2 = 0.9531$ and time to failure (t) = 1043 hr. From equation (1), the MTTF of the two-parameter Weibull distribution is calculated as follows:

$$\text{MTTF} = \boldsymbol{\eta}\,\Gamma\,(1 + \frac{1}{\beta})$$

$$\text{MTTF} = 1977.5312 \text{ X } \Gamma\,(1 + \frac{1}{2.8065}) = 1977.5312 + \Gamma\,(1.36)$$

Using the gamma functions table, Γ (1.36) = 0.89018

Hence, MTTF = 1977.5312 X 0.89018 = 1760.36hr

The failure rate of the two-parameter Weibull distribution is calculated using equation (2) as follows:

$$\lambda(t) = \frac{\beta}{\eta}\,(\frac{t}{\eta})^{\beta-1} = \frac{2.8065}{1977.5312}\,(\frac{1043}{1977.5312})^{2.8065-1} = \frac{2.8065}{1977.5312}\,(\frac{1043}{1977.5312})^{1.8065}$$

= 0.0014192 x 0.31484 = 0.0004468/hr.

The failure rate of the marine diesel engine crankshaft is estimated to be 0.0004468/hr. Applying equation (3), the reliability of the marine diesel engine crankshaft is calculated as follows:

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}}$$

$$e^{-(\frac{1043}{1977.5312})^{2.8065}}$$

$$= e^{-(0.52743)^{2.8065}}$$

$$= e^{-(0.1661)}$$

R(t) = 0.846962 = 0.84696

Table 3. Two-parameter Weibull estimates

Shape parameter (β)	Scale parameter (η)	Coefficient of correlation (ρ)
2.8065	1977.5312	0.9763

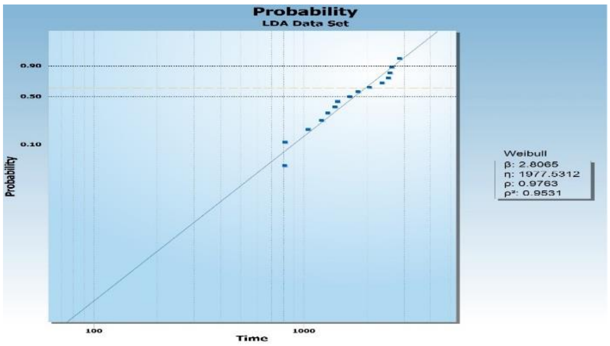

Figure 1. Probability plot

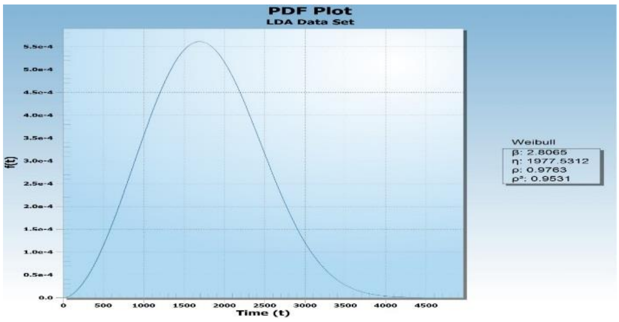

Figure 2. Plot of PDF against time

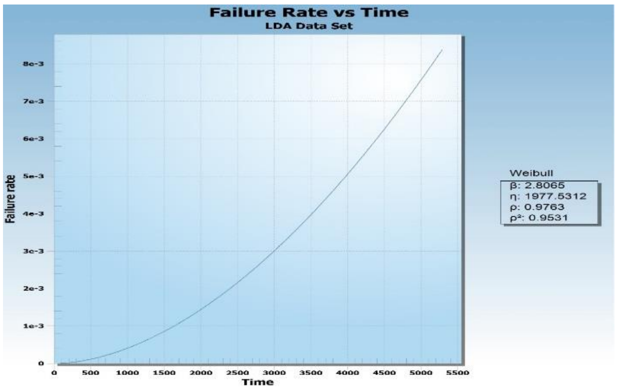

Figure 3. Failure rate against time

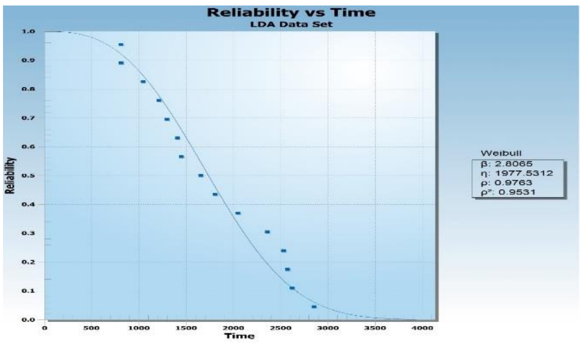

Figure 4. Plot of reliability against time

Discussion of result

In this study, two parameter distribution using the median rank regression estimation method is used to analyze the failure times of the marine diesel engine crankshaft. Figure 1 illustrates the probability of failure over time. From the plot, it is obvious that the Weibull distribution function $F(t)$ is a linear function of t. This means that our data was adequately described by the two-parameter Weibull distribution. Figure 2 shows the plot of the two-parameter probability density function (PDF) over time, t. From the plot, the shape of the probability density function of the Weibull distribution is observed to be symmetrical and bell-shaped, just like the normal distribution. The probability density function steadily increases until it gets to its mode at time, t=1,680 hr., after that point, it can be seen to be decreasing gradually. The plot of the failure rate against time is shown in Figure 3. In Figure 3, the failure rate of the Weibull distribution can be seen increasing over time, t, which is indicative that the crankshaft is in its early fatigue periods. At this point, the crankshaft is beginning to experience wear and tear as a result of friction as poor quality of lubricating oil contribute to such greatly. In Figure 4, the reliability plot of the two-parameter Weibull distribution is shown. From the plot, a gradual drop in reliability is noticed as the time to failure increases. It is a well-known fact that no matter how well a component or system is designed or manufactured or maintained; it is bound to fail at some point during its operating life. The drop in the reliability of the marine diesel engine crankshaft is therefore expected as it has been in operation for a long time and running hours of a component also dictates the lifespan of the component.

The estimates of the two-parameter Weibull distribution, namely the shape and scale parameter ($\boldsymbol{\beta}$ and $\boldsymbol{\eta}$) and the correlation coefficient, ρ, were calculated using reliability software, TPC Windchill quality solutions 11. The following results were obtained: $\boldsymbol{\beta} = 2.8065$, $\boldsymbol{\eta} = 1977.5312$ as shown in Table 3. The value of correlation coefficient, $\rho = 0.9763$, shows that there is a good linear fit for the Weibull distribution. This means the rank regression method provided a good measure of fit as a strong correlation is observed in the crankshaft in its early wear-out period as $\boldsymbol{\beta} > 1$. This also means that the failure rate of the crankshaft is gradually increasing as the journal bearings and crankpin are continuing to wear due to friction (arising from poor lubricating system or poor quality of lubricating oil), misalignment and improper grinding. The values of the shape and scale parameters obtained in our analysis were used to compute the MTTF, failure rate and reliability of the marine diesel engine crankshaft using equations (1-3) and the following results were obtained: MTTF = 1760.36hr, $\lambda(t) = 0.0004468$, and $R(t) = 0.84696$.

Conclusion

The application of the two-parameter Weibull distribution method to assess the reliability of the Mitsubishi S&U marine diesel engine crankshaft has been investigated. The study involves the analysis of the failure times of the crankshaft using the median rank regression estimation method. Their failure times were rank-ordered and estimates of the two-parameter Weibull distribution; shape and scale parameters were determined using TPC Windchill quality solutions 11. This estimation method was found to be effective and accurate than the manual approach. The value of the correlation coefficient obtained in the study showed that the two parameters by Weibull distribution were suitable for fitting the data points. The value of the shape parameter, $\boldsymbol{\beta} = 2.8065$ obtained is greater than 1. The MTTF, failure rate and reliability were successfully computed using the values of the shape and scale parameters obtained. The reliability of the crankshaft was found to be about 84.696%.

Competing Interests

Authors have declared that no competing interests exist.

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