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The Small Sample Failure Distribution Model of Diesel Engine Component Parts Using the FMECA Approach

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Abstract—**This paper aims to provide a way to deal with the small sample related to failure data for reliability based on FMECA approach. In order to help optimize the reliability of products using a systematic method, a theoretical approach is applied, starting from the traditional theory of failure mode effects analysis (FMEA). Then a novel small sample failure distribution parameter estimation which employs the least square method and the maximum likelihood method is proposed, and their estimation values under the same situation are compared. The least square estimation is validated to be more efficient than the maximum likelihood parameter estimation and thus is more suitable for the model building. Based on the reliability data from the database of our research group, the distribution model of the critical diesel engine component is developed. Finally, a distribution is implemented, which can obtain the failure probability density function curve and the failure rate curve.**

Index Terms—**Failure distribution, failure mode effects and criticality analysis , small sample.**

I. INTRODUCTION

Researches on reliability problems originated in the United States, the department of military aviation realized the cost of plane failure was too large, thus the reliability was put forward [1], then various researches have been investigated [2]. Product design and maintenance that only relies on experience often leads to more optimization and development. Reliability research not only provides the direction of reliability improvement for quality development, but also helps ensure the logistics organization to improve the service level [3]. In terms of reliability analysis, the data source from actual operation is an important factor to assess the reliability of the engine [4]. Through comprehensive analysis of the collected failure data, it is tenable to obtain the distributing rules of engine and its parts, distribution function or life function as well as some reliability certification indexes, such as failure rate, average life expectancy and so on. At the same time, basic analysis can also be combined with FMECA, reliability allocation and reliability forecast, which are all beneficial to enhance product quality and provide valuable basis to reliability investigations.

In practice, the FMECA approach becomes widely used in reliability research area soon after it is proposed attributed to the significance of its estimation results. The analysis process and design attention of FMECA are discussed from the view of methodology which leads to an improved approach based on the original one [5]. Using modern computer technology to manipulate the large amounts of FMECA data that stored in a computer database improves the efficiency and accuracy greatly, its automation avoids unnecessary faults [6].Applying FMECA to production processes may find out critical failure modes [7]. An integrated FMEA method is proposed to establish a evaluation model of strong operation ability which has sequenced the failure modes after the foundation of FMEA is discussed [8].In addition to FMECA approach, quantitative reliability index has great importance to the reliability of the evaluation and improvement in this academic field. So it is necessary to introduce a distribution model to fit the failure data by experiments, Weibull distribution is the most common one in the product estimation especially automobile components such as the diesel engine. However, its estimates are more difficult to ensure compared with the index distribution model as there are three parameters in this model, while the least square method and the maximum likelihood method can satisfy it well.

II. DIESEL ENGINES AND PARTS FMECA

A. Reliability Analysis of the Purpose and Content

The aim of reliability analysis is to assess the diesel engine reliability using the support of reliability data combined with failure mode effects and criticality analysis (FMECA).This is achieved by mathematical modeling and calculation which are able to find out the fault location, modes, frequency of causes, and the critical components of the product from a reliability perspective based on the early data collection. The core of this work is the criticality analysis, used to evaluate the harmfulness of each failure mode and find the severity of each part to the whole engine. Then it uses the analysis to develop, in more detail, the corrective standards of assessment and evaluation of engine quality and reliability useful for the following optimization.

B. Engine and Parts Failure Analysis Method

Failure analysis is mainly aimed at reliability of engine and key subsystems or components, more detailed program of reliability studies are carried out as follows.

1) Engine failure analysis

The engine fault analysis aims to evaluate which are the most critical combination failures (cause-mode-effect, obviously using FMECA) that the product could suffer, so as to find out the direction of the reliability improvement research, also to put forward corresponding optimization measures. According to the steps of FMECA, it is able to predict the influences to the reliability of engine key subsystems, patterns, causes and so on by using the statistics of failure frequency under presented conditions. Analyzing

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the distribution of fault location in the high-level components dendrogram when the data is small can find out the fault components of higher frequency, as the data set grows, it gradually extends to the lower-levels parts, which provides conditions for deep studies of effect and criticality analysis.

In order to improve the engine quality, component parts that are most harmful to product reliability based on fault location frequency analysis should be improved. Similarly some more critical failure modes are concluded based on the analysis of failure modes, which are the targets to eliminate next step, furthermore, sequencing the fault modes and criticality using comprehensive comparison evaluation could finally find fault modes needed to improve. Obviously, targeted eliminating or improving optimizes the level of design and reliability.

2) Parts failure analysis

Component parts failure analysis main aims to analyze fault frequency of all kinds of engine parts of various levels under every condition, in order to find out the key failure modes and causes of these parts, to put forward the improvement measures and Suggestions helpful for improving the quality of the product. For the engine failure analysis conclusion, the frequency queue of the various failure positions determines the component object of parts failure analysis, especially these top frequency failure parts could be the key of the analysis.

It is applied to every components of diesel engine, to whole product or to parts, even to specific levels of the product structure tree, and to statistics of key auto components and parts according to fault frequency table. Then to research the cause of high frequency of the problem as well as to find out the primary cause of failure supports the design's development and optimization in order to satisfy the functional and reliability requirements, in terms of customer needs.

C. Engine FMECA

This engine FMECA is based on the engine fault analysis module, which is included in the database system, it will be discussed in another paper, following analysis is focus on failure modes, positions and criticality.

1) Failure position and mode analysis

The statistical data of the diesel engine failure positions is presented in Table 1, and histogram statistics are shown in Fig. 1. There are significant differences between the frequencies of different diesel engine fault positions, also failure frequency of each subsystem is easily distinguished. The top of the frequent fault parts are fuel pump (13.978%), supercharging device (12.096%), starter (10.483%) and so on. The three parts account for 36.4% of the total engine failure, particularly the fuel injection pump breaks down most frequently, so it is notable that fuel pump is the primary factor that influence the reliability of a diesel engine, improving the level of its reliability has the highest priority for the diesel engine.

TABLE I: FREQUENCY OF THE DIESEL ENGINE FAILURE POSITIONS

Failure position	Frequency/time	Frequency（%）
Fuel injection pump	52	13.978
Supercharging device	45	12.096
Starter	39	10.483
Fuel pipe	13	3.4946
Exhaust pipe	11	2.9569
Thermostat	11	2.9569
Fuel injector	10	2.6881
DC motor	9	2.4193
Flywheel	9	2.4193
Piston rings	8	2.1505

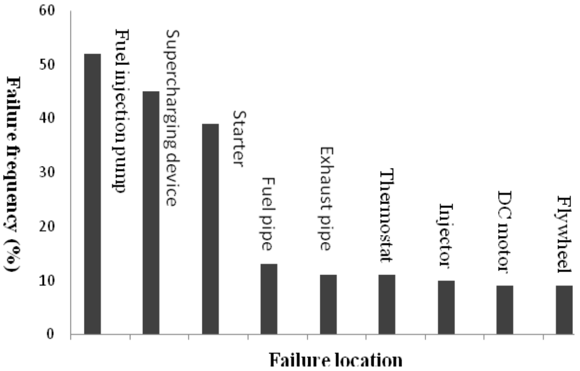

Fig. 1. Frequency of the diesel engine failure positions.

The statistical data of the diesel engine failure modes is presented in Table II, and histogram statistics are shown in Fig. 2. Obviously, frequencies of failure modes are relatively concentrated，especially，the top of the frequent fault modes are oil or water leak (21.774%), function failure (17.204%), oil channeling (7.258%) and so on. The three modes account for about half of the total engine failure, these several failure modes need to be emphatically analyzed later, which means to obtain the failure causes and criticality prepared for a targeted design and deeper research.

TABLE II: FREQUENCY OF THE DIESEL ENGINE FAILURE MODES

Failure mode	Frequency/time	Frequency（%）
oil or water leak	81	21.774
function failure	64	17.204
oil channeling	27	7.258
abnormal noise	27	7.258
maintenance	19	5.1075
overheating	12	3.2258
performance degradation	12	3.2258
air leak	9	2.4193
clamping stagnation	8	2.1505
fatigue fracture	8	2.1505

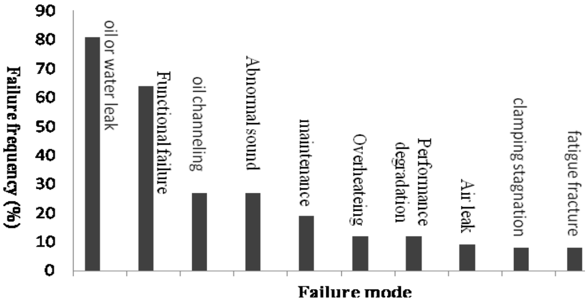

Fig. 2. Frequency of the diesel engine failure modes.

From the preliminary analysis the failure modes and positions are revealed. Failure of fuel injection pump occurs most frequently, which is the primary factor of reliability evaluation of the diesel engine, then supercharging device, starter, oil tube and exhaust pipe have a high incidence. Simultaneously, failure modes occur more frequently are oil or water leak, function failure, oil channeling, abnormal noise, maintenance, overheating, performance degradation.

After failure position and mode analysis of engine, the following failure criticality analysis of components needs to be discussed.

2) *Criticality analysis*

The criticality analysis is aimed to find the most critical issues in terms of reliability, e.g. failure modes, failure causes and components. These are using quantitative comparison combined with modeling analysis.

Criticality of failure mode C_{mj}

$$C_{\mathrm{mj}} = \alpha_j \bullet \beta_j \bullet \lambda_p \bullet t \tag{1}$$

where α_j is the frequency ratio of failure modes, when the total of failure modes is N, the total of α_j is 1. And **N** represents the total number of failure modes of the product.

$$\sum_{1}^{N} \alpha_j = 1 \tag{2}$$

β_j represents the influence probability of failure modes β=1,0.1~0.5,0~0.1,0 mean loss, more possible lose, possible lose and no effect, respectively. λ_{p} is the failure rate. t is the work hours of product.

$$C_{\mathrm{r}} = \sum_{j=1}^{N} C_{mj} = \sum_{j=1}^{N} \alpha_j \bullet \beta_j \bullet \lambda_p \bullet t \tag{3}$$

C_{r} is the criticality of the product, which is the summation of C_{mj} above. In order to calculate the criticality of each component parts in the product, this formula is transformed to get the influence coefficient of the ith components to the whole engine.

$$C_{ri} = \sum_{i=1}^{n} \sum_{j=1}^{N} \alpha_{ij} \bullet \beta_{ij} \bullet \overline{\lambda} \tag{4}$$

where α_{ij} is the frequency ratio of failure modes of the ith components. And n represents the total number of failure modes of the ith components.

$$\alpha_{\mathrm{ij}} = {}^{n_j}\!/_{N} \tag{5}$$

n_j represents the frequency of the jth failure mode of the ith components.

$$\overline{\lambda} = \lambda_{\mathrm{p}} \bullet t = \frac{N_i}{\sum t} \tag{6}$$

$\overline{\lambda}_{\mathrm{i}}$ is the average failure rate of the ith components and N_{i} is the total of failure.

The statistical data come from the reliability database that has been established by us which include failure information in 1.5 years, so the cumulative working time of component parts t is assumed as 13140 hours. Then average failure rates of top 10 failure positions are obtained.

$$\begin{aligned}\overline{\lambda}_{\mathrm{i}} = [&0.003957382\,0.003424658 \quad 0.002968037\\ &0.000989346 \quad 0.000837139\\ &0.000837139 \quad 0.000761035\\ &0.000684932 \quad 0.000684932]\end{aligned}$$

With this information it is easy to work out the criticality of each component parts, this is shown in Table III.

TABLE III : THE CRITICALITY OF COMPONENT PARTS

component parts	criticality	component parts	criticality
Fuel injection pump	0.001325	Exhaust pipe	0.000854
Starter	0.001305	Thermostat	0.000788
Supercharging device	0.001301	Flywheel	0.000647
Fuel injector	0.000997	DC motor	0.000554
Fuel pipe	0.000875		

Obviously, some high frequency failure parts effect more on the reliability of the diesel engine, however, some low frequency failure parts are not necessarily less harmful to the product, such as the exhaust pipe and so on. These parts usually lead to serious consequences, for example function failure, hence the lifetime of these parts must be extended. That requires a deeper study.

III. THE SMALL SAMPLE FAULT DISTRIBUTION MODEL

A. *Law of Failure Under Small Samples*

With the frequency sequencing of failure positions developed, it is worth mentioning that the law of failure distribution is tenable to predict the failure frequency in the future which has a great reference value for guiding the corresponding logistics organizations.

However, because the amount of test data is small, it is difficult to obtain ideal results by conventional parameter estimation method. Not only general methods are not useful for exploring its regularity, but also Weibull distribution is not suitable for small sample cases, some parts of fault estimation, so we need to take a targeted approach for small samples in order to obtain better prediction results.

Here we take exhaust pipe for example, the reliability database filters some failure data including 13 fault record, as the sample size is smaller than 20, so we adopt several methods to study the failure distribution regularity in small sample situation.

B. *Exhaust Pipe Failure Distribution Parameter Estimation*

The exhaust pipe that located between the exhaust manifold and the muffler plays an important role in noise elimination, vibration reduction and prolonging service life of the system. Its main failure modes are air leak , oil channeling, fatigue crack and fatigue fracture.

The failure mileage of the exhaust pipe follows Weibull distribution through empirical hypothesis.

$$F(\mathrm{t}) = \int_{\infty}^{t} f(x)dx = 1 - \exp\left[-\frac{(t)^m}{t_0}\right] \tag{7}$$

To take the exhaust pipe failure data from the reliability database as the sample, they are sorted in ascending order as shown in table 4. When the sample size of exhaust pipe failure is less than 20, the cumulative failure probability can be calculated using the median rank.

TABLE V : THE FAILURE MILEAGE OF THE EXHAUST PIPE

failure mileage /km	failure mileage /km	failure mileage /km
3596	20780	87079
6332	21200	110320
10696	24469	131443
20594	52777	
20594	62463	

$$F(\mathrm{t_i}) = \frac{i-0.3}{n+0.4}(\mathrm{i}=1,2...,n) \tag{8}$$

where i and n represent the sequence number and sample size, $t_1<t_2 \ldots < t_3$ are the experimental data. Additionally, in order to obtain better estimates, we compare the parameter estimation results of least square method with maximum likelihood method to choose the best estimates.

1) *Least squares estimation*

This step starts with linear transformation of the Weibull distribution by the correlation coefficient method, which results with a linear equation. And after linear transformation of sample data, we get a training set.

$$y=bx+a \tag{9}$$

$$T=\{(\mathrm{x}_1,y_1),(x_2,y_2),\ldots,(x_n,y_n)\} \tag{10}$$

Table V indicates that a scatter plot is available. Figure 3 is shown as satisfying nearly linear distribution in addition to individual cases.

TABLE V : THE MEDIAN RANK AND THE TRAINING SET

T_i	F_i	X_i	Y_i	Least squares estimation	Maximum likelihood parameter estimation
3596	0.0522	8.19	-2.93	0.059923	0.05424633
6332	0.1269	8.75	-2	0.104041	0.095229572
10696	0.2015	9.28	-1.49	0.170753	0.158036966
87079	0.7985	11.37	0.47	0.793956	0.777236843
110320	0.8731	11.61	0.72	0.865922	0.853020378
131443	0.9478	11.79	1.08	0.909391	0.8995357

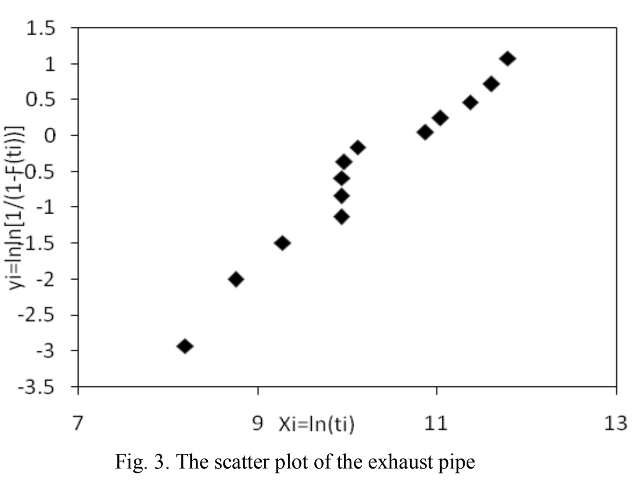

Fig. 3. The scatter plot of the exhaust pipe

Then through the least square method, parameter estimates of (9) are calculated as $\mathrm{a}=-10.925$, $\mathrm{b}=1.017$.

The linear equation is $\mathrm{y}=1.017x-10.925$.

The correlation coefficient is R^2=0.968. It is significantly correlated.

So we can obtain the parameters of failure distribution.

$$\begin{cases} \mathrm{m}=1.017 \\ t_0=e^{10.925}=555.47.845 \end{cases}$$

2) *Maximum likelihood parameter estimation*

The theory of maximum likelihood method is widely applied. If random variable ε follows the distribution of $\mathrm{f}(x;p)$, then to choose some samples $(\varepsilon_1,\ldots\varepsilon_\mathrm{n})$ from it, the probability of observed values is $P=P(\mathrm{p};x)$, this expression of p is seen as a function of the unknown parameters. $L(\mathrm{p})=L(\mathrm{p};x_1,\ldots x_n)$ represents the likelihood function. We try to obtain the largest probability of observed values in the sampling, meanwhile, the likelihood function has its extremum. Also the failure samples follow 2-parameter Weibull distribution through empirical hypothesis as proposed above. Thus, *lnL(p)* is regarded as the objective function.

$$\ln L=L(\mathrm{m},t_0;x_1,\ldots x_n) \tag{11}$$

We can get $\ln L=L(\mathrm{m},t_0;x_1,\ldots x_n)$ after the logarithm of (11). The next step is to take partial derivatives with respect to m and t_0 respectively. The parameter estimation values are $m=1.03327, t_0=58753.14$.

C. *Comparison of Different Methods*

There are some differences between the results of the maximum likelihood method and the least square method, it needs a comparison to find out the best estimates.

Table 6 shows parameter estimation values and normalized root mean square error (NRMSE) of two methods. Obviously, NRMSE of maximum likelihood parameter estimation is bigger, so least square method is better in this term.

TABLE VI: COMPARISON OF PARAMETER ESTIMATIONS

parameter estimations	least square method	Maximum likelihood method
m	1.017	1.03327
t_0	55547.845	58753.14
NRMSE	0.0776	0.0801

$$NRMSE=\sqrt{\frac{\sum_{i=1}^{n}\left[\tilde{F}(t_i)-\tilde{F}(t_1)\right]^2}{\sum_{i=1}^{n}\tilde{F}^2(t_i)}} \tag{12}$$

In order to make fitting results more intuitive, fitted curves plotted by MATLAB are shown in Fig. 4.

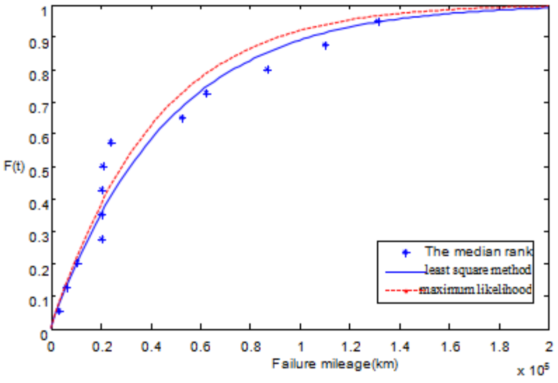

Fig. 4. Comparison of fitted curves.

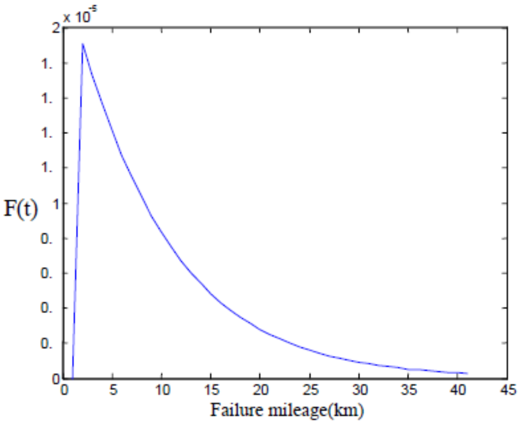

Fig. 5(a). The failure probability density function curve.

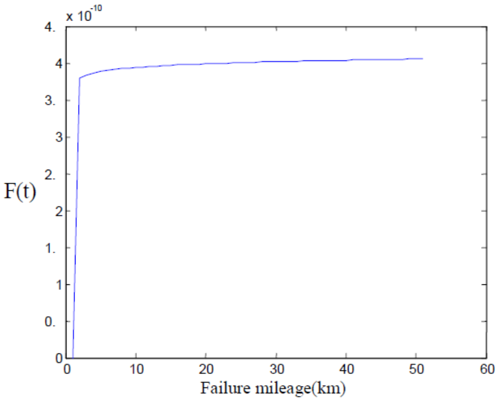

Fig. 5(b). The failure rate curve.

Through these comparison, we choose the least squares estimation as the final distribution parameters, the failure distribution model of exhaust pipe is established as follows.

$$F(t)=1-\exp\left[-\frac{t^{1.017}}{55547}\right] \tag{13}$$

The failure probability density function curve and the failure rate curve are presented in Fig. 5a and Fig. 5b. It can be seen that the failure rate is increasing, which means the product are in wearing malfunction period.

IV. CONCLUSIONS

This paper points out how parameter estimation has been integrated with known reliability techniques, such as FMECA, to find out an roadmap for small sample distribution modeling. First, a parts failure analysis and criticality analysis method is applied to obtain the most critical issues from low frequency failure parts. Then the efficiency of the least square estimation is verified to be higher than that of the maximum likelihood parameter ESTIMATION. AT LAST, THE DISTRIBUTION MODEL OF THE CRITICAL diesel engine component is developed on basis of our calculations, hence, the failure probability density function curve and the failure rate curve. We hope the work presented in this paper is beneficial to the development of reliability improvement.

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