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METODA PRZEWIDYWANIA NIEZAWODNOŚCI ELEMENTÓW SKŁADOWYCH SILNIKA DIESLA OPARTA NA ANALIZIE PRZYCZYN I SKUTKÓW USZKODZENIA FMEA

A RELIABILITY PREDICTION METHOD FOR DIESEL ENGINE COMPONENTS BASED ON FMEA

Przewidywanie niezawodności polega na ocenie niezawodności urządzeń lub wyrobów z użyciem modeli i danych matematycznych przed wejściem tych pierwszych do produkcji lub ich modyfikacją, zanim dostępne są dane empiryczne. Jest to ważna część działań mających na celu poprawę niezawodności, jakie prowadzi się podczas całego czasu eksploatacji danego systemu. Artykuł koncentruje się na zagadnieniu przewidywania niezawodności elementów składowych silnika Diesla. Dla skrócenia czasu gromadzenia potrzebnych informacji oraz poprawy skuteczności predykcji zaproponowano metodę zintegrowaną z analizą przyczyn i skutków uszkodzenia (FMEA). Metoda stanowi modyfikację metody podobieństwa konstrukcyjnego (design similarity), w której niezawodność nowego elementu składowego oblicza się porównując występowanie przyczyn jego uszkodzeń w nowej konstrukcji z ich występowaniem w podobnym, już istniejącym elemencie składowym. Proponowaną metodę omówiono na przykładzie predykcji niezawodności uszczelki głowicy cylindra silnika o zapłonie samoczynnym.

Słowa kluczowe: *przewidywanie niezawodności, silnik Diesla, podobieństwo konstrukcyjne, FMEA.*

Reliability prediction involves reliability estimation of equipment or products prior to their production or modification by applying mathematical models and data before empirical data are available. It is an important part of reliability improvement work in the whole lifetime of a system. This paper focuses on the reliability prediction of diesel engine components. To reduce the time of gathering useful information and to improve prediction efficiency, a method integrated with design failure mode and effects analysis (FMEA) is proposed. The method is a modification of design similarity method in which the reliability of a new component is calculated by comparing its failure modes occurrence in the new design with the one of a similar existing component. An example about reliability prediction of a cylinder head gasket in a diesel engine is used to illustrate the proposed method.

Keywords: *Reliability prediction, diesel engine, design similarity method, FMEA.*

1. Introduction

A diesel engine is an internal combustion engine that uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion chamber during the final stage of compression. It has been widely used in automobiles, vessels, military vehicles, electrical generators, etc [14]. As an important factor, reliability is taken into account through the whole lifetime of diesel engines. Reliability modeling and prediction of the engine has been one of the most important issues in the engine manufacturing industry.

Many engineers have made significant efforts on improving reliability of diesel engine or its components. Liu and Huang [11] discussed the evaluation of diesel engine using general reliability indexes and automobile specific reliability indexes based on maintenance records. Arcidiacono and Campatelli [1] developed an approach called failure mode and effect tree analysis (FMETA), which is the combination of axiomatic design, FMEA and fault tree analysis (FTA). FMETA can be used to evaluate the Risk Priority Number (RPN) for a component of the product and to find the reliability relation among its components. The method has been validated by an application to an automotive heavy-duty diesel engine. Jardine and Ralston [9] examined whether or not prognostics and health management (PHM) could improve the accuracy of the oil-analyst/expert system in determining the risk of failure of a diesel engine used on Canadian Pacific Rail.

Reliability prediction deals with evaluation of a design prior to actual construction of the system [3,16]. Although the product reliability is not increased by the prediction process, the result of reliability prediction provides an early indication as to whether a design is likely to meet reliability goals, points to potential reliability problem areas in a new design or design modifications, and identifies components needing further testing. It is a tool to determine as early as possible whether the equipment will be reliable enough or whether it needs further improvement to function successfully for the company [2, 5,15].

It is highly desirable to obtain precise prediction of the reliability of a new product before it is manufactured. System-level reliability predictions are generally developed based on a system model and component-level reliability prediction [6-8, 12, 18]. Component-level reliability can be determined from a variety of sources [17]. Traditional reliability prediction approach is based on reliability block diagram (RBD). Three commonly used prediction techniques are part count method, stress analysis method and design similarity method. The part count method approximately produces the prediction on the number of parts in the proposed design. The stress analysis method evaluates designs by comparing predicted strengths with anticipated stresses. The design similarity method analyzes similar systems currently in operation and uses the results to predict the reliability of a proposed design. This requires a careful comparison of components to determine which are truly comparable in the new design and a separate evaluation for those that are not. It also requires valid and reliable data on the performance of the similar components [17].

The design similarity method is usually used in the early design phase. For a diesel engine, most designs are modifications on the basis of existing ones. There is no natural distinction between new and existing designs except absolutely fresh technology is presented. Although there is a limited amount of information about new design, information about similar designs can always be found, providing important references for reliability prediction of new types of diesel engine.

Failure Modes and Effects Analysis (FMEA) is methodology for analyzing potential reliability problems early in the development cycle where it is easier to take actions to overcome these issues, thereby enhancing reliability through design. FMEA has been paid more attention in many diesel engine manufacturing industries. If the reliability information provided by FMEA can be taken full advantage in reliability prediction, it is possible to decrease the time for gathering data and then improve prediction efficiency.

Research studies on reliability prediction integrated with FMEA have been focused by scholars in recent years. Jin and Tu [10] established a reliability prediction model integrated with FMEA considering different effects of each failure mode. Yang et al (2008) developed a fuzzy rule-based Bayesian reasoning approach for prioritization of failures in FMEA on a rational basis [19]. Reliability prediction values and mean time between failure (MTBF) are calculated using criticality scales. The method proposed in Reference [12] is suitable for the detailed design phase. When using this method, a great deal of information about the product is needed. The accuracy of prediction relies on the validity of FMEA.

In this paper, a reliability prediction model based on FMEA and design similarity is proposed. In the design phase of a new type of diesel engine, reliability prediction can be executed according to FMEA of similar existing types. The difficulty of evaluating defects number is overcome by evaluating failure modes occurrence of similar existing items. The paper is organized as follows. In Section 2 design similarity method considering variation of fault rate is discussed. In Section 3, a method for estimating reliability using FMEA occurrence is proposed. A case study about a cylinder head gasket of a diesel engine is given to show the prediction process. Section 5 gives a brief summary.

2. Reliability prediction using design similarity method

New diesel engines are always developed on the basis of existing ones, a great deal of similarities exist between them although there are some variations. Design similarity method utilizes fault rates of existing components to predict fault rates of new products [13]. The failure rate of an existing component can be obtained from sources such as company warranty records, customer maintenance records, component suppliers, or expert elicitation from design or field service engineers.

Defects in a component are imperfections that cause inadequacy or failure. The imperfections are always caused by shortcomings in the design and manufacture process. The relationship between failure rate and defect number is expressed as follows [13]:

$$\lambda_o = m \cdot d_o \quad (1)$$

where λ_o is the failure rate of existing similar components, d_o denotes the total number of known defects, and m is a coefficient. The failure rate of the new component is calculated as follows:

$$\lambda_n = m \cdot d_n \quad (2)$$

where λ_n is the failure rate of the new component, d_n is the total defects number of the new design:

$$d_n = d_o + d_i - d_e \quad (3)$$

where d_i is the total number of new defects caused by design modification, d_e is the total number of eliminated defects by design modification. According to Eq. (1), Eq. (2) and Eq. (3), the failure rate of the new component can be calculated as:

$$\lambda_n = \lambda_o \cdot \left(\frac{d_o + d_i - d_e}{d_o}\right) \quad (4)$$

The difference between the failure rates of the new and existing products is defined as $\Delta\lambda$, then:

$$\Delta\lambda = \lambda_o - \lambda_n = k \cdot \lambda_o \quad (5)$$

where k represents the coefficient considering the reliability improvement because of design modification. Then:

$$\lambda_n = \lambda_o - \Delta\lambda = \lambda_o \cdot (1 - k) \quad (6)$$

and Eq. (4) can be rewritten as:

$$\lambda_n = \lambda_o \cdot \left(1 - \frac{d_e - d_i}{d_o}\right) \quad (7)$$

By comparing Eq. (6) and Eq. (7), the relationship between k and defects number is given as follows:

$$k = \frac{d_e - d_i}{d_o} \quad (8)$$

After determining the values of d_o, d_e and d_i, the coefficient k can be obtained. Then the failure rate of the new subsystem/component can be calculated according to Eq. (7).

After predicting the reliability value of each component, the reliability of the diesel engine system can be estimated on the basis of the reliability block diagram model, which is expressed in Eq. (9):

$$\lambda_s^* = \sum_{i=1}^{N} \lambda_i^* \quad (9)$$

where λ_s^* refers to reliability prediction value of the diesel engine system, and λ_i^* refers to the reliability value of the ith component.

When using design similar method. It is often difficult to obtain defects number exactly in engineering practice. This motivates us to find a relatively feasible method to estimate the defects number.

3. Estimation of k on the basis of FMEA

FMEA (Failure Modes and Effects Analysis) is used to identify potential failure modes, determine their effects on the operation of the product, and identify actions to mitigate the failures. Design FMEA is methodology for analyzing potential reliability problems early in the design phase where it is possible to take actions to reduce design defects by modification. It is a product design verification activity that can help avoid a large percentage of product design problems before the design is finalized. While anticipating every failure mode is not possible, the development team should formulate a list of potential failure modes as extensively as possible [4].

A failure mode is the manner by which an equipment or machine failure is observed. It generally describes the way the failure occurs. In FMEA, occurrence is ranked according to the failure probability, which represents the number of failures anticipated during the design life of an item. The range of values and the linguistic terms used to describe the frequency of the failure mode occurrence are shown in Table 1 [4].

Failure modes can be observed and represented by occurrence，and failure modes can be considered as defects representations of the subsystem (assembly or components). In this paper, we try to find the relationship between occurrence and defects number to estimate the value of *k*. The aim is to obtain creditable reliability prediction through making good use of design FMEA result, to reduce the time for gathering valid reliability information, and to increase the prediction efficiency.

According to table 1, there exists a nonlinear relationship between failure rate and occurrence rank. It is not possible to produce a linear function of occurrence rank. By multiplying the failure rate by eight, the relationship can be transformed to linear. The transformed scale of failure rate is also shown in table 1. The defects number of existing items is estimated by:

$$d_o = \sum_{j=1}^{N} D_j, \quad j = 1,2,...,N \tag{9}$$

where N is the failure modes number of existing diesel engine components, D_j is the transformed scale of the jth failure mode occurrence in design FMEA. After design modification, the total number of new defects is given as:

$$d_i = \sum_{t=1}^{M} D_t, \quad t = 1,2,...,M \tag{10}$$

where M is the total number of new failure modes caused by design modification, D_t is the transformed scale of the tth new failure mode occurrence in design FMEA. The eliminated defects number is given as:

$$d_e = \sum_{k=1}^{P} D_k, \quad k = 1,2,...,P \tag{11}$$

where P is the total number of failure modes eliminated by design modification, D_k is the transformed scale of the kth eliminated failure mode occurrence. Then the factor k can be calculated using Eq.(8).

4. Case study

A cylinder head gasket is a gasket that sits between the cylinder block and cylinder head in a diesel engine. It is an integral component of the engine and the most critical sealing application in any engine. The cylinder head gasket must maintain the seal around the combustion chamber at peak operating temperature and pressure. The gasket must seal against air, coolants, combustion and engine oil at their respective peak operating temperature and pressure. The materials used and design employed must be thermally and chemically resistant to the products of combustion and the various chemicals, coolants and oils used in the engine [14]. Design FMEA form of a cylinder head gasket is shown in Table 2, in which five failure modes are considered.

In the design process of a new type of diesel engine on the basis of previously used ones, suppose that design modification is made by increasing the flange of cylinder block. The aim is to decrease the occurrence of "Gas leakage" and to reduce the performance degradation probability subsequently. However, the design modification causes a new potential failure mode, shown in Table 3.

We can execute the reliability prediction process of the cylinder head gasket according to Table 2 and Table 3. The steps are shown as follows:

(1) Calculate the sum of transformed scales of five failure modes in the previously designed diesel engine:

$$d_o = 0.004+0.004+0.00005+0.00005+0.004=0.0121$$

(2) Calculate the sum of transformed scales of potential failure modes in the new design:

$$d_i = 0.00005$$

Tab.1. Frequency of occurrence evaluation criteria of diesel engine

Rank	Occurrence	Description	Potential failure rate	Transformed Scale
1	Very low	Failure is unlikely	≤1/1500000	0.000005
2	Low	Relatively few failures	about 1/150000	0.00005
3			about 1/15000	0.0005
4	Moderate	Occasional failures	about 1/2000	0.004
5			about 1/400	0.02
6			about 1/80	0.1
7	High	Repeated failures	about 1/20	0.4
8			about 1/8	1.0
9	Very high	Failure is almost inevitable	about 1/3	2.7
10			≥1/2	4.0

Tab. 2. Design FMEA of cylinder head gasket

Item	Failure modes	Failure causes	Failure effects	O	S	D	RPN	Recommended actions
cylinder head gasket	Gas leakage	creep deformation, fatigue, unreasonable flange dimension	overheat, performance degradation	4	8	3	96	increase flange width of cylinder block, modify specifications
	water leakage	gasket ring over age,, relative small cylinder mold, defective materiel	cylinder head surface corrosion	4	6	3	72	increase tightness
	Small location hole diameter	Nonstandard design	cylinder block cannot be installed	2	6	2	24	strictly control dimension, tolerance, productive process
	Big location hole diameter	Nonstandard design	cylinder block displacement	2	6	2	24	
	Unreasonable cylinder diameter	Unreasonable dimension chain Wrong sickness	blasting pressure increase, performance degradation	4	8	3	96	

Tab. 3. A potential failure mode of new diesel engine

Item	Failure mode	Failure cause	Failure effect	O
cylinder head gasket	water leakage	cylinder block cannot be installed	displacement caused by relative bigger flange width	2

(3) Calculate the sum of transformed scales of eliminated failure modes in the new design:

$$d_e = 0.004$$

Then the factor k can be obtained according to Eq. (8):

$$k = \frac{d_e - d_i}{d_o} = \frac{0.004 - 0.00005}{0.0121} = 0.3264$$

Supposed that the failure rate of the previously designed cylinder head gasket is $\lambda = 5.505 \times 10^{-8}$, the failure rate of the cylinder head gasket in the new design is calculated by Eq. (6):

$$\lambda_n = \lambda_o \cdot (1 - k) = 3.7079 \times 10^{-8}$$

Failure rates of other components can be obtained according to above steps based on the design FMEA occurrence. Finally the failure rate or reliability of the whole diesel engine can be estimated using Eq. (9).

5. Conclusions

New types of diesel engine are formed based on design modification of existing ones, and the engine structures are not usually changed in a great extent. In the design stage, detail design FMEAs are always executed for existing types and the analysis documents are preserved permanently. For new designs, potential failure modes are predicted at least. By comparing design FMEA results of existing and new design, it is possible to conclude that some failure modes in the existing types are eliminated, and some new failure modes are presented by design modification.

The reliability prediction method discussed in this paper utilizes FMEA to increase the efficiency of reliability prediction. Through comparing FMEA of existing and new design, changes of failure modes and of failure modes occurrence scales are obtained. Then the factor which characterizes the change of failure rate can be calculated. When there exists a great deal of difference between new and existing designs, the method in this paper cannot be employed with confidence.

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This research was partially supported by the National High Technology Research and Development Program of China (863 Program) under the contract number 2007AA04Z403, and the Open Project Program of the Key Laboratory of Manufacture and Test Techniques for Automobile Parts (Chongqing University of Technology), Ministry of Education, Chongqing, 400050, China.

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