MTBF estimation of a new design reactor coolant pump

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Abstract: This paper presents an approach for the MTBF estimation of a new design reactor coolant pump (RCP). The proposed approach is based on failure mode and effects analysis (FMEA) and path classification and estimation (PACE) model. FMEA is used to identify and classify the failure modes of the new design RCP, and compare them to the reference products to find the similar parts. The exemplars affiliated to the Category 3 failures of the similar parts will be selected from the reference products to construct a PACE model. The remaining useful life (RUL) of the new design RCP after a limited test time can therefore be estimated by the PACE model. A general equation for the MTBF estimation of a new design RCP is also presented. Since the proposed method is based on real performance data from reliability test, it will provide more accurate MTBF estimation than classic methods.

Keyword: reliability estimation; failure mode and effect analysis; PACE model; reliability testing

1 Introduction

Reactor coolant pump (RCP) removes heat from reactor by driving the coolant circulation in the reactor coolant system (RCS) of a nuclear power plant (NPP). A RCP has to satisfy a special demand in mean time between failures (MTBF) in view of the crucial roles it plays in both safety and economy of a NPP.

A new type of shaft seal RCP for the ACP1000 Hualong No. 1 Reactor has been designed and is now under manufacturing. As one of the reliability requirements, the RCP is expected to operate for 20,000 hours continuously without failure.

Traditionally, statistical methods can be applied to estimate the MTBF of a product, which will require a sufficiently large number of samples for life testing, or abundant historical data of faults obtained from real operation. However, for a very complicated mechanical and electrical product like RCP, the required conditions for statistical analysis are usually not available, especially for a new design product.

This paper presents a FMEA and PACE model based approach for the MTBF estimation of a new design RCP by smaller samples and lesser test time.

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2 Classic methods for MTBF estimation

2.1 Statistical method

Traditionally, the MTBF of a product can be estimated by the following statistical method using the data from life testing with a sufficiently large sample of the products.

$$MTBF = \sum_{i=1}^{N} T_i \Big/ N \qquad (1)$$

Where N is the total number of samples;
T_i is the time-to-failure of the i^{th} sample.

However, for a new design RCP, this method is not applicable because there will be no sufficient samples available for a lifespan test because both a RCP and its lifespan test are all costly.

2.2 Reliability model method

Given the failure rate of a product is $\lambda(t)$, then MTBF of the product can be calculated by the following equation.

$$MTBF = \int_0^\infty e^{-\lambda(t)} dt \qquad (2)$$

Assume that the MTBF of RCPs follows an exponential distribution, then

$$MTBF = \frac{1}{\lambda} \qquad (3)$$

However, the failure rate of a new design RCP is also unknown. The following equation can be used for estimating the failure rate of a product, but it will also face the problem of less samples.

$$\lambda(t) = \frac{\Delta r(t)}{\left[N - r(t)\right]\Delta t} \tag{4}$$

Here, $r(t)$ is the number of products that have already been failed before time point t, $\Delta r(t)$ is the number of products that failed during a time span of Δt after time point t.

2.3 Parts count method

If a product consists of n components, then the failure rate of the product can be estimated as:

$$\lambda = \sum_{i=1}^{n} \lambda_i \tag{5}$$

Where λ_i is the failure rate of the i^{th} component.
If a component has multiple independent failure modes, the failure rate of a component is equal to the sum of the failure rate of each failure mode. One of the major merits of this method is that the failure rate of each component might be available from statistical tests or empirical prediction methods. However, the failure rate of the RCP might be overestimated because not every failure mode of a component may cause the RCP to fail. In other words, the MTBF estimation of a new design RCP by this method will be rather conservative. In addition, the improper design, process weakness, as well as interaction failures between components are in general not taken into account.

2.4 Physics of failure method

Physics of failure method focuses on the major failure modes of a product. Based on a deep understanding of the failure phenomena and mechanisms of the product, the simulation technology or a derived quantitative model can be utilized for an accurate MTBF estimation. However, since this method will not provide a universal expression of the failure model of the product, there will be no ready-made quantitative model available for estimating the MTBF of a new design RCP. Lack of life testing and operational experience is an obstacle to having deep insight into the failure mechanisms of a new design RCP and to deriving a quantitative failure model for it.

2.5 Similar equipment method

Similar equipment method is based on the engineering experience that a new design product may have a similar reliability to the reference product if they have the same or similar functions, components, structures and operating conditions. This means that the MTBF of a new design RCP can be estimated if the similar equipment exists and its reliability level has already been known. The estimation accuracy will be determined by how similar a new design RCP is to its reference equipment. Dealing with the differences between a new design RCP and its similar equipment is crucial for improving the estimation accuracy.

3 MTBF estimation of a new design RCP

As discussed in Section 2, the MTBF estimation by classic methods may not yield a satisfied result. This paper presents a methodology for a better MTBF estimation of a new design RCP by comprehensively utilizing above mentioned classic methods with Failure Mode and Effects Analysis (FMEA) and Remaining Useful Life (RUL) estimation technologies.

3.1 Failure mode and effects analysis

FMEA is a bottom-up, inductive analytical method to chart the probability of failure modes against the severity of their consequences. Usually FMEA classifies the severity of failures into 4 categories.

Category 1: The failure is catastrophic which could result in death or permanent total disability of the product.

Category 2: The failure is critical which could result in permanent partial disability of the product.
Category 3: The failure is marginal which could result in a performance reduction of the product.

Category 4: The failure is negligible which will lead to extra maintenance works of the product.

Due to the importance of a RCP in the safe operation of a NPP, if a Category 1 or Category 2 failure occurs in a RCP, the RCP has to be shut down immediately. In this case, the remaining useful life (RUL) can be considered as zero. If a Category 3 failure occurs, such as material deformation, crack or fatigue, the RCP may not fail immediately. Instead, it could continue to work until the performance degradation exceeds the predefined threshold. The Category 4 failures can be negligible for estimating the MTBF because they have no effect on the performance of the product. Therefore, the MTBF of a RCP can be estimated by the following model.

$$MTBF = \frac{1}{\sum_{\forall i,j} \lambda_{iC_{1j}} + \sum_{\forall i,k} \lambda_{iC_{2k}} + \Lambda_{C_3}} \quad (6)$$

Where $\lambda_{iC_{1j}}$ is the failure rate of the j^{th} Category 1 failure mode of the i^{th} component, $\lambda_{iC_{2k}}$ is the failure rate of the k^{th} Category 2 failure mode of the i^{th} component, Λ_{C_3} is the equivalent failure rate of the Category 3 failure of the product.

For a new design RCP, it is relatively easier to obtain the failure rate data of the Category 1, Category 2 and Category 3 failures through various life testing of components and by statistical methods. However, it will be difficult for the component manufacturers to provide Λ_{C_3} because

(1) The component manufactures have no means for implementing a large number of full system tests to observe the effects of a single Category 3 failure on the remaining useful life of a RCP, and

(2) The Category 3 failures may interact with each other.

If Λ_{C_3} is simply taken Λ_{C_3} as the sum of the failure rates of all Category 3 failures, then the estimation result will be rather conservative.

3.2 PACE model[1-2] for estimating the equivalent failure rate of Category 3 failures

The product performance may degrade because of Category 3 failures. Path classification and estimation (PACE) model is used to estimate the UL or RUL of an individual product entirely based on performance data of products instead of statistical data. As shown in Fig.1, assume that a group of the degradation signals with respect to time $U_i(t)$ (values of parameters) and their associated failure times T_i of products can be collected.

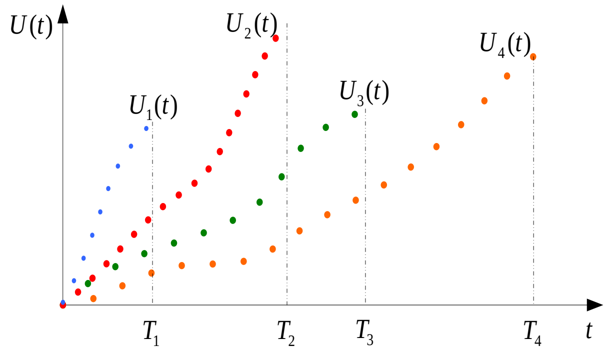

Fig.1 Example degradation signals.

As shown Fig.2, the failure modes can be generalized as degradation paths by fitting an arbitrary function to the performance data via regression, machine learning, *etc.*

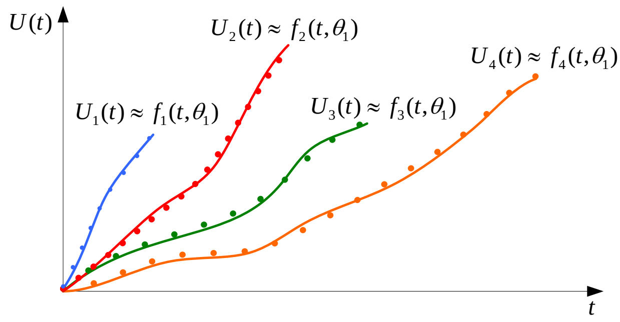

Fig.2 Functional approximations of example degradation signals.

There are two useful pieces of information that can be extracted from the degradation paths, *i.e.*, the failure times and the "shape" of the degradation. These pieces of information can be used to construct a vector of exemplar failure times and functional approximations, as follows:

$$T = \begin{bmatrix} T_1 \\ T_2 \\ \cdots \\ T_n \end{bmatrix} \qquad f(t,\Theta) = \begin{bmatrix} f_1(t,\theta_1) \\ f_2(t,\theta_2) \\ \cdots \quad \cdots \\ f_n(t,\theta_n) \end{bmatrix} \quad (7)$$

Where, T_i and $f_i(t,\theta_i)$ are the failure times and functional approximation of the i^{th} exemplar degradation path, θ_i are the parameters of the functional approximation of the i^{th} exemplar degradation path, and Θ are all of the parameters of each functional approximation.

The estimation of RUL for a new design RCP by PACE model is fundamentally composed of the following procedures:

(1) Identify similar products with plenty of degradation signals from the existed RCPs in NPPs as references.

(2) Collect exemplars of the Category 3 failures' degradation signals and failure times from the reference products.

(3) Construct a vector of exemplar failure times and functional approximations.

(4) Obtain the degradation signals from the new design RCP as a test sample. The degradation signals can be obtained from for example a 500 hours reliability identification test.

(5) Evaluate the test sample for estimating the expected values of the degradation signal at the current time t^* according to the exemplar degradation paths.

$$f(t^*,\Theta)=\begin{bmatrix} f_1(t^*,\theta_1) \\ f_2(t^*,\theta_2) \\ \cdots \quad \cdots \\ f_n(t^*,\theta_n) \end{bmatrix} \tag{8}$$

The function evaluations can be interpreted as exemplars of the degradation signal at time t^*. In this context, equation (8) can be rewritten as follows:

$$U(t^*)=\begin{bmatrix} f_1(t^*,\theta_1) \\ f_2(t^*,\theta_2) \\ \cdots \quad \cdots \\ f_n(t^*,\theta_4) \end{bmatrix}=\begin{bmatrix} U_1(t^*) \\ U_2(t^*) \\ \cdots \quad \cdots \\ U_n(t^*) \end{bmatrix} \tag{9}$$

At the same time, the current t^* is used with the vector of failure times to calculate the expected RULs of the sample according to the exemplar degradation paths.

$$L(t^*)=T-t^*=\begin{bmatrix} T_1-t^* \\ T_2-t^* \\ \cdots \quad \cdots \\ T_n-t^* \end{bmatrix} \tag{10}$$

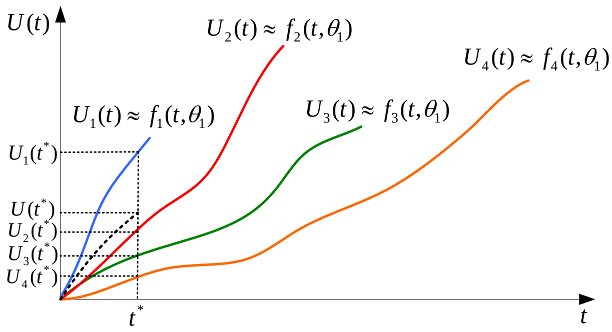

Fig.3 Product's degradation signal at time t^* relative to the functional approximations of the exemplars.

(6) Compare the observed degradation signal values of the sample to the expected degradation signal values to obtain a vector of memberships:

$$\mu_U\left[u(t)^*\right]=\begin{bmatrix} \mu_{U_1}\left[u(t)^*\right] \\ \mu_{U_2}\left[u(t)^*\right] \\ \cdots \quad \cdots \\ \mu_{U_n}\left[u(t)^*\right] \end{bmatrix} \tag{11}$$

(7) The memberships and the failure times of exemplars are combined in some way to estimate the RUL of the new design RCP at time t (marked as $RUL_S(t)$), such as a simple weighted average.

(8) The equivalent failure rate of the Category 3 failures of the similar parts can be therefore estimated by:

$$\Lambda_{SC_3}=\frac{1}{t+RUL_S(t)} \tag{12}$$

4 Discussion

A new design RCP will be out of question different from its reference products more or less. The accuracy of RUL estimation by PACE is greatly related to the selection of reference products and the collection of exemplar degradation signals. For reflecting the effect of the differences between a new design RCP and its reference products on the estimation of MTBF, the following three key factors are further taken into account to modify Eq. (12).

(1) Similarity

The exemplar degradation signals from much more similar products in all aspects may help to obtain a better estimation of MTBF. In order to find the most similar products, the similarity degree of the new design RCP to its reference products much be clearly identified by comparing the FMEA report of the new design RCP with that of the reference products carefully.

(2) Fault Coverage

Fault coverage is another key factor in deciding how long a reliability test of the new design RCP should be conducted to expose its degradation characteristics sufficiently. The fault coverage also reflects to what extent the Category 3 failure modes of the similar parts can be covered by the exemplars. A reliability test with higher fault coverage will have a greater value of reference for the MTBF estimation.

(3) Diversity

It is clearly that the new design RCP will be partially similar to its reference products. Difference of the new design RCP with its reference products may come from design, material, process level and working conditions, *etc*. The effects of these differences on the MTBF estimation should be considered.

Note that RUL_p of a new design RCP is derived only from the similar parts of its reference products. Therefore, the equivalent failure rate of Category 3 failures can be divided into two parts:

$$\Lambda_{C_3} = \alpha \cdot \Lambda_{C_3} + (1-\alpha) \cdot \Lambda_{C_3} \ , \ \alpha = \frac{m}{n} \qquad (13)$$

Where m is the number of Category 3 failures in the similar parts of the new design RCP, n is the total number of Category 3 failures of the new design RCP. Thus, α is a metric of similarity that represents the similarity of a new design RCP with its reference product. α=1 means the new design RCP is exactly same as its reference product, while α=0 means that the new design RCP is absolutely different from the reference product.

Further considering not all Category 3 failures can be exposed during the reliability test, the equation (13) can be modified as follows:

$$\Lambda_{C_3} = \alpha \cdot \beta \cdot \Lambda_{C_3} + (1-\alpha \cdot \beta)\Lambda_{C_3} \qquad (14)$$

Where β is a metric of fault coverage. β=1 indicates that the Category 3 failures in the similar part are fully exposed during the reliability test and fully covered by the exemplars, while β=0 means no Category 3 failures will be exposed during the reliability test, or the exposed Category 3 failures are not covered by exemplars.

The term $\alpha \cdot \beta \cdot \Lambda_{C_3}$ represents the equivalent failure rate of Category 3 failures in the similar part that can be exposed in the reliability test at time t and covered by the exemplars, it can be estimated by the PACE model.

$$\alpha \cdot \beta \cdot \sum_{\forall i,l} \Lambda_{iC_{3l}} = \frac{1}{t + RUL_S(t)} \qquad (15)$$

Thus, the equivalent failure rate of Category 3 failures of the new design RCP will be:

$$\Lambda_{C_3} = \frac{1}{\alpha \cdot \beta \cdot [t + RUL_S(t)]} \qquad (16)$$

Finally, above equation can be further revised by considering the differences between the new design RCP and its reference product as follows.

$$\Lambda_{C_3} = \frac{\gamma}{\alpha \cdot \beta \cdot [t + RUL_S(t)]} \qquad (17)$$

Here γ is a metric of diversity that reflects the effects of the differences between the new design RCP and its reference product on the failure rate prediction. γ=1 represents that there is no difference between the similar part of the new design RCP and its reference product; $\gamma > 1$ represents that comparing with the reference product, the reliability of the similar part of the new design RCP is improved; $\gamma < 1$ represents that comparing with the reference product, the reliability of the similar part of the new design RCP is decreased.

Thus the final equation for the MTBF estimation of a new design RCP based on PACE model method is:

$$MTBF = \left\{ \sum_{\forall i,j} \lambda_{iC_{1j}} + \sum_{\forall i,k} \lambda_{iC_{2k}} + \gamma \cdot \{\alpha \cdot \beta \cdot [t + RUL_S(t)]\}^{-1} \right\}^{-1} \qquad (18)$$

It is clear that if the new design RCP is exactly same as its reference products, i.e., α=1, β=1 and γ=1, then equation (18) will be equal to equation (6).

5 Conclusions

RCP is a very complicated mechanical and electrical facility which is crucial to the safe operation of nuclear power plants. For a new design RCP, the MTBF estimation by classic methods will be inapplicable because there will be not enough samples available for longtime life testing.

This paper presents an approach by FMEA and PACE model for the MTBF estimation of a new design RCP. FMEA is used to identify and classify the failure modes of the new design RCP and compare them to the reference products to find the similar parts. The failure rate of each Category 1 and Category 2 failure mode can be obtained by reliability test at component level because there will be no useful life available for a RCP once such kinds of failures occur. The exemplars affiliated to the Category 3 failures of the similar parts will be selected from the reference products to construct a PACE model. Real operating data of the new design RCP from a reliability test can be used for estimating the RUL corresponding to the comprehensive effects of Category 3 failures in the similar parts. A general equation for the MTBF estimation of a new design RCP is also presented by considering three factors, that is, similarity, fault coverage and diversity, to reflect the differences in design, material, process, manufacture, *etc*. Given the exemplars are plenty enough, the effects of Category 3 and even Category 4 as well as their combinations on MTBF can be effectively reflected in the estimation of RUL by PACE model. The proposed method for MTBF estimation is simply and easier to implement. Since the proposed method is based on real performance data, it will provide more accurate than classic methods.

It can be seen that the lower similarity and fault average will result in a worse estimation of MTBF. Therefore, selecting more similar product with plenty of exemplars of failures which can over the Category 3 failures as much as possible, and conducting a reliability test to making the Category 3 failures fully exposed and covered by the exemplars will help improve the accuracy of the MTBF estimation for a new design RCP.

List of Acronyms

ACP1000	Advanced China Pressurized Water Reactor 1000 MW
FMEA	Failure modes and effects analysis
MTBF	Mean time between failures
PACE	Path classification and estimation
RCP	Reactor coolant pump
RCS	Reactor coolant system
RUL	Remaining useful life
UL	Useful life

References

[1] HINES, J.W. and GARVEY, D.R.: Nonparametric Model-Based Prognostics, Proceedings of Reliability and Maintainability Symposium, Las Vegas, USA, 2008, pp. 469-474, Annual. IEEE, 2008.

[2] CHEN, J., SONG, C.W., QI, X.Y., and WU, W.: “Path Classification and Estimation Model based Prognosis of Pneumatic Cylinder Lifetime,” Chinese Journal of Mechanical Engineering, Vol. 22, No.2, pp. 392-397, 2012.