Reliability prediction of electromechanical system concerned about correlation of multiple failures based on RFD

D Y Ma¹, G Sun², J M Gao¹, R X Wang¹*, P F Zhang², K Chen¹ and Z Wang¹

¹State Key Laboratory for Manufacturing Systems Engineering, Xi’an Jiaotong University, Xi’an 710049, China
²STATE GRID Corporation of China, Beijing 100031, China

Corresponding author and e-mail: R X Wang, rongxiwang@163.com

Abstract: As the boosting complexity of developing electromechanical system in various fields, significant efforts have been recently devoted to the reliability analysis of electromechanical system to obtain better precision of reliability prediction, leading to advanced demand of reliability prediction methodologies. Conventional system reliability prediction adopts the reliability prediction theory of electronic products which ignores the interaction among different components. Aiming at this, an improved reliability calculation approach concerning correlation is proposed in this paper, taking dependence into account by considering the correlation degree between the primary and the secondary failure modes of components as the main factor in reliability prediction by building failure modes reliability prediction HOR (house of reliability) of components.

1. Introduction

With the continuous improvement of the number and complexity of components in electromechanical system, the basic reliability of the system must be guaranteed to achieve higher reliability. It is known that reliability analysis is of great importance and efforts have been made to this field. In Ref [1], crude Monte Carlo simulation is performed to analyze a gear systems in shearer mechanisms. Jian et al. proposed a LS-SVM model to analyze the global characteristics of complex slopes during reliability analysis procedure [2]. Wang et al. proposed a novel method of condition recognition by combining complex network theory with phase space reconstruction to recognize the different conditions of an electromechanical system [3], which make contribution to reliability analysis. Based on the time-dependent system reliability analysis, in Ref [4], the system resilience was estimated. Zhang et al. [5] proposed a four-step framework to deal with the condition that information about the condition of a system and its components is often available in text form when reliability assessment of the system is conducted. Jan et al. [6] discussed different RFD determination results for several common protection configurations for more accurate system reliability analysis.

The purpose of system reliability prediction is to estimate the index of reliability during the stage of reliability design in order to lay a foundation for the optimization of the design. Liu et al. [7] proposed an optimized design among different parameter sets to optimize the design of the LC filters from a reliability perspective. As a reverse to reliability allocation, reliability index gained from it is then compared to the original index of reliability in order to find the weakness in the system in order to correct the designing scheme by adjusting relevant parameters. So the accuracy and timeliness should
firstly be improved. Common reliability prediction method of electronic system is classified as methods of similar analysis, statistical analysis[8, 9] and failure physical analysis[10, 11]. Reliability prediction method used in electromechanical system mainly contains mathematical model[12], performance parameter[13], top and bottom limitation, failure rate[14], stress analysis, simulation[15] and Monte Carlo[16]. In recent years, some researchers have assessed the mechanical diagnosis reliability such as Takasaki et al.[17]. Zhu et al. proposed a new Kriging-based reliability method whose general process is similar to that of Kriging and Monte Carlo Simulation.[18]

Contribution of this paper is to propose a new reliability prediction method based on RFD (reliability function development). Through the reliability prediction, an error in design is found accurately and a recommendation for improvement is proposed.

2. Correlation concerned reliability calculation model of series system

2.1. Reliability model of electromechanical system in series

1) Reliability model of electromechanical system in series

Being composed of multiple components, electromechanical system fails when an error happens to any one of the components. Its reliability block diagram is showed as Figure 1.

![Figure 1](image1)

**Figure 1.** The reliability block diagram of parts in series.

2) Reliability model of components in electromechanical system in series

Construction of multiple failure modes leading to the fault of a specific corresponding component can also be considered as a series system. Its reliability block diagram is showed in Figure 2.

![Figure 2](image2)

**Figure 2.** The reliability block diagram of failure mode in series.

2.2. Primary theory of reliability calculation for electromechanical system in series

1) Independence assumption theory

\[ R = R_1 R_2 \ldots R_n = \prod_{i=1}^{n} (1 - F_i) \]  \hspace{1cm} (1)

In the formula, R represents system reliability or component or part reliability; \( R_i \) represents component or part or failure reliability; \( F_i \) represents failure possibility, \( F_i = 1 - R_i \); \( n \) represents the number of components or failure. Obviously, formula (1) doesn’t consider the correlation.

2) Vulnerable spot theory

This theory is showed by formula (2).

\[ R = \text{Min} R_i \hspace{1cm} (i = 1, 2, \ldots, n) \]  \hspace{1cm} (2)

In the formula, \( n \) represents the number of the unit belonging to the system.

2.3. Improved correlation concerned reliability calculation theory

The ordinary limitation theory has simple calculation procedure however it also has a wide boundary. The second order narrow boundary theory has a more precise conclusion but a large computation. So a method concerning correlation is needed. Components reliability calculation based on primary and secondary failure mode correlated

If a part has \( n \) failure modes with \( n \) reliability indexes of \( \beta_1, \beta_2, \ldots, \beta_n \), and \( \beta_1 \leq \beta_2 \leq \ldots \leq \beta_n \) and the
corresponding reliabilities are $R_1 \leq R_2 \leq \ldots \leq R_n$, being that $R_1$ and $R_2$ are the primary and the secondary failure mode. Then:

$$
R = \frac{1}{2} \left[ 1 + \prod_{i=3}^{n} R_i \right] \left[ R_2 - (1 - R_2) \phi \left( \frac{R_1 - \rho_{12} \rho_{22}}{\sqrt{1 - \rho_{12}^2}} \right) + (1 - R_1) \prod_{i=3}^{n} R_i \phi \left( \frac{\rho_{12} \rho_{22}}{\sqrt{1 - \rho_{12}^2}} \right) \right]
$$

(3)

In the formula, $R$ represents the reliability of components; $\rho_{12}$ represents the correlation index between the two failures.

3. Multi-failure correlated reliability prediction of components in electromechanical system

3.1. Construction of a reliability prediction space of failure modes

The first question when designers carry on the reliability prediction concerned about correlation has to be faced is how to identify the primary and the secondary failure mode and get their reliability index prediction value.

Aiming at the above problems, this paper sets up HOR group of components failure reliability prediction, based on the FMECA analysis. The HOR group composes the reliability prediction space, as showed in the followed Figure 3.

**Figure 3.** The reliability prediction space of failure modes

3.2. Setting up failure mode reliability prediction HOR and its calculation mode.

Reliability prediction HoR has a Matrix Structure. The matrix of relationship of failure mode and failure mechanism is used to describe the relevancy of failure mechanism. The weight vector of failure mechanism represents the accuracy rate of it. Weight of the failure style reveals whether the failure is soft or hard.

The higher a failure mechanism has the accuracy rate, the more likely it is a hard failure, the more prior it will be. The first and the second are the primary and the secondary failure mode.

Finally transfer the priority of failure to the reliability index correction factor, use the reliability prediction HOR to find the solution.

In the case of the original value of the reliability index known, considered as the input of the failure mode reliability prediction HOR, $\beta$ is used in the calculation of the predicted value of every reliability index. If failure mode $j$ is independent, its priority can be represented as:
\[ CL_j = p_j \times \sum_{i=1}^{n} (w_i \times u_{ij}) \quad (j = 1, 2, \ldots, m) \] (4)

In the formula, \( p_j \) represents the style of the jth failure mode; \( w_i \) represents the accuracy probability weight of the ith failure mechanism; \( u_{ij} \) represents the correlation index of the failure i and failure j; \( n \) is the number of the failure mechanisms; \( m \) is the number of the failure mode. Normalized CL will be the \( \gamma_j \). The reliability of every failure mode \( \beta_j^* \) is calculated by the follow equation:

\[ \beta_j^* = \gamma_j \times \beta_0 \] (5)

In the formula, \( \beta_0 \) is the basic value of failure mode of the components. It is also the original value of reliability index.

In order to distribute the whole reliability to failure modes, it is supposed that the reliability of every failure mode equals. So the whole reliability will be shared equally among all failures firstly. Those equal reliabilities are called basic reliability. It is named \( R_{j0} \).

\[ R_{j0} = \sqrt[1/n]{R} \] (6)

Under the assumption that the stress and strength accord with the normal distribution, the value of \( \beta_0 \) according to \( R_{j0} \) can be figured out referring to the normal distribution table.

4. Demonstration
In this paper, reliability of the transmission system of a machine tool is used as the object of the study.

4.1. Reliability prediction of components
After the FMECA (failure mode effective criticality analysis) analysis, we find out the failure modes of every components, and through the original data we get the original value of reliability index. Because of the limit of the article length, they are not presented in article.

The failure mode of the rolling bearing is completely independent of other relevant parts in this case. Therefore, in this case, the gear, shaft and its accessories is estimated.

Limited to the space, the sliding gear which have the lower original value of reliability belonging to axes III is analyzed to predict the reliability of it. The reliability prediction HOR is established as shown in Figure 4.

![Figure 4. The reliability prediction HOR](image-url)
After the above matrix calculation, it is known that teeth surface pitting and teeth surface abrasion are the first two failure mode in priority, they have the lowest predicted value of reliability index. Obviously, teeth surface pitting should be deemed as the primary failure mode and teeth surface abrasion should be considered as the secondary failure mode and their function. According to the correlation calculation, the correlation coefficient between the primary and the secondary failure modes is figured out—\( \rho_{12} = \rho_{21} = 0.8077 \). So far, reliability data of every failure mode of the sliding gear is obtained as shown in the followed table.

| Name                        | Overload fracture | Teeth surface abrasion | Teeth surface pitting | Fatigue fracture | Plastic deformation |
|-----------------------------|-------------------|------------------------|-----------------------|------------------|---------------------|
| Reliability index           | 3.42              | 2.89                   | 2.61                  | 2.65             | 3.42                |
| Reliability                 | 1                 | 0.9981                 | 0.9953                | 0.9960           | 1                   |
| Correlation coefficient of the primary and the secondary failure modes | 0.8077            |                        |                      |                  |                     |

Then data in Table 1 should be plugged into formula (3) to calculate the predicted reliability value of the sliding gear in \( 10^3 \)h—\( R=0.994195 \), the corresponding value of MTBF is 171764h, the particular reliability is in the range calculated from the ordinary boundary theory. That is \( R_{\text{min}} = 0.9894 \leq R \leq R_{\text{max}} = 0.9953 \).

### 4.2. Transmission system reliability prediction

Because of the independence of bearing failure, during the calculation procedure, the reliability of a system composed by components except bearings should firstly be solved, then the reliability index \( R_s \) of the whole system should be solved according to reliability prediction theory of series system.

The primary and the secondary failure modes are sliding gear and spline shaft. Next, the function of them should be established according to the flow path of reliability prediction concerned about correlation.

According to the improved theory, the correlation coefficient can be determined as \( \rho_{12} = \rho_{21} = 0.30181 \). The predicted value of the system except bearing is \( R = 0.967067 \).

Using independence assumption, considering 15 bearings as a series system, its reliability is \( R' = 0.883291 \). According to reliability calculation of series system, the transmission system reliability in \( 10^3 \)h service period is \( R_s = R \times R' = 0.967067 \times 0.883291 = 0.854202 \).

The predicted calculation MTBF value of transmission system is 6345h (switched from the value of reliability), which is higher than the allocation value of reliability. The reasons are as shown: 1. The predicted reliability value of some of the components is on the high side due to the lack of historic data in using reliability manual and the assumption of ideal condition of the work coefficient. 2. In order to prevent fatal accident, support bearings before and after the spindle are precision double row cylindrical roller bearings (NNU49/630SK.M.SP, NNU49/630SK.M.SP) with plenty reliability margin.

### 5. Conclusions

In this study, reliability models of electromechanical system in series on the level of components and system were both established. Moreover, a new approach of reliability prediction was proposed based on FMECA analysis and RFD (reliability function development) to take multiple failure modes into account. Firstly, the primary value of reliability must be figured out in handbook and experimental data or concluded from similar product. Secondly, the relationship between failure modes and failure
mechanism was estimated and the failure mode should be evaluated both in probability and form, on which the calculation of the predicted value of reliability was based. Finally, on the basis of the calculation of the primary and the secondary failure modes and components, the reliability of components and system can be predicted by the reliability prediction method concerned of correlation. The verification of the new method was presented by a demonstration utilizing the transmission system of the headstock of a heavy turning machine which indicated that more accuracy of reliability prediction was obtained on condition of considering the correlation. The result showed that the method proposed is able to find the weak point in the system, so it can be used to predict reliability more precisely.

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