Comprehensive Deployment Method for Technical Characteristics Base on Multi-failure Modes Correlation Analysis

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Abstract. This paper put forward a new method of technical characteristics deployment based on Reliability Function Deployment (RFD) by analysing the advantages and shortages of related research works on mechanical reliability design. The matrix decomposition structure of RFD was used to describe the correlative relation between failure mechanisms, soft failures and hard failures. By considering the correlation of multiple failure modes, the reliability loss of one failure mode to the whole part was defined, and a calculation and analysis model for reliability loss was presented. According to the reliability loss, the reliability index value of the whole part was allocated to each failure mode. On the basis of the deployment of reliability index value, the inverse reliability method was employed to acquire the values of technology characteristics. The feasibility and validity of proposed method were illustrated by a development case of machining centre's transmission system.

1. Introduction

The cause of the failure for mechanical parts simultaneously comes from the failure mechanisms [1-3], the soft failures and the hard failures, just like wear degradation, corrosion, fatigue, fracture, overload and so on. Failure modes can be divided into soft failures and hard failures. There are complicated correlative relations between failure mechanisms and failure progresses, interlocking failures from one part may show a network spreading phenomenon just like the spreading of failures in electromechanical system [4]. For a long time, due to lacking of effective tools for describing and analysing the complicated relations above, there is a disconnect between reliability design and performance design, that makes deployment values of design parameters cannot guarantee the reliability of products.

Reliability design is closely related to uncertain factors, the design method rely on probability was widely used in mechanical reliability design after the general method first/second-order reliability was put forward [5, 6]. The stress-intensity interfere model based on probability[7] is a reliability design method which is general used at present time, researchers have made a lot of studies on the method for calculating the reliability of parts and systems. However, in practical application, the analysing tools like FTA, FMEA/FMECA[8-10] and so on which are used in the stress-intensity interfere model have their limitations such as the expression is not rigorous, lack of consistency and they only consider

single failure mode, especially not considering the correlations between failure modes[11]. Meanwhile the method above is only for the main failure mode for probability design, which ignores the correlation between multiple failure modes. That makes it unreasonable.

In the nineties of the 20th century, the concept of reliability function deployment (RFD) emerged, it makes up the lack of QFD technology[12] in product planning with considering the product failures and their impact[13]. The article [14] makes qualitative and quantitative description, analysis for the fault propagation path and trend between components using the domino matrix in RFD, and improves the traditional reliability deployment method based on it. It can be found the advantage of RFD is that it converts the reliability analysis method from filling in the forms to analysing the matrix structure correlation, controlling product reliability from top to bottom using the method of decomposing matrixes. RFD's matrix structure can indicate different processing level for the system complexity, the description for the relation between design factors is clearer and more concise. Meanwhile, RFD process also can use the numeric operations and normalization method existing in QFD for numerical operation. So using RFD matrix structure to describe correlations of failure mechanisms and failure modes has the advantages of tight expression and convenient calculation, and it can effectively evaluate and calculate the interrelated effect of multiple failure modes.

In summary, this paper, which is aiming at overcoming the limitation of traditional method, puts forward a comprehensive deployment method for technical characteristics considering the interrelated and coupled relations between failure modes. First, build a reliability deployment space for failure modes which is made up with houses of reliability. Second, comprehensive considering the interrelation between failure modes, the total reliability index value is decomposed and allocated to failure modes of the part. Next, establish a connection equation or limit state equation, build the technical characteristics deployment space, solve the design parameters of technical characteristics using the inverse reliability method [15, 16]. Last, considering interrelated effect of design parameters of parts, the deployment design parameters are imported into the space for matching design parameters and weakening conflicts, output the final deployment value.

2. Build the house of reliability and synthetically allocating the technical characteristics
In order to considering the correlative effects of different failure modes, the house of reliability will be established. And through complex processes, the reliability index of one part or component will be allocating to the design parameters finally.

2.1. 2.1   Build the house of reliability for failure modes
The relation of failure mechanisms, hard failures and soft failures is shown in figure 1. It can be found that there are complex relationships between failure modes and failure mechanisms. Meanwhile it can be concluded that the reliability losses caused by different failure modes are different.
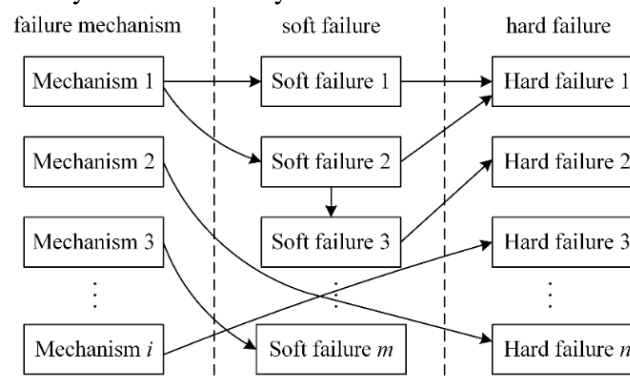
Figure 1. The relation between failure mechanism, hard failure and soft failure

This paper only establishes the failure mode reliability deployment house according to some main failure mechanisms. The reliability deployment house consists of three matrices:

(a) Relationship matrix between failure mechanism and failure mode of parts, $\mathbf{U}\{u_{ij}\}$.

The element u_{ij} expresses the relationship between failure mechanisms and soft and hard failure modes. In this paper, the assessment value of u_{ij} is divided into weak, medium and strong three grades, respectively take the integer 1, 3 and 9.

(b) Failure mode autocorrelation matrix, $\mathbf{P}\{p_{ij}\}$.

The element p_{ij} represents the correlation coefficient between failure mode p_i and p_j on the same component.

(c) Reliability loss weight matrix of failure mechanisms, $\mathbf{W}\{w_i\}$.

The element w_i represents the magnitude of the loss of reliability caused by failure mechanism i, it can be obtained by the evaluator according to the relevant reliability statistics. The weight is expressed by integers 1 to 9, according to the reliability loss from small to large.

2.2   Comprehensive deployment process for technical characteristics

According to the basic principles of RFD, and considering the interaction of the design value of technical characteristics. The whole process can be divided into the following three stages:

(a)   First phase, on the basis of product reliability allocation and FMECA analysis, the failure mode reliability allocation of each component is established to construct the failure mode reliability deployment space. And the reliability loss of each failure mode is calculated with the matrix structure of the failure mode reliability deployment house of each component. According to the size of the reliability loss, the reliability index values are assigned to the failure modes of the component, and output the main failure mechanisms corresponding to each failure mode.

(b)   Second phase, input the results of the first phase, the comprehensive deployment space of the technical characteristics of each part was established. In this space, the connection equation or the limit state equation is established for the main failure modes of each component according to its main failure mechanisms, and the design parameter value can be found.

(c)   Third phase, input the result of the second phase, and the matching and conflict resolution space for design parameters is established. In this space, according to certain rules, the deployment design parameters of each part are matched and resolved conflicts, and get the final design parameter deployment value.

The above configuration process is integrated with the RFD theory, inverse reliability method based on probabilistic design and the conflict resolution technique, and the reliability design process of mechanical parts is integrated into staged data processing and calculation process. By using the matrix decomposition structure of RFD method, the reliability index of part is further allocated to various failure modes, finally, the inverse reliability method is used to establish the mapping relationship between reliability index and mechanical component design parameter, which makes the reliability design and performance design of mechanical parts more closely integrated, so the process are systematic, hierarchical and practical.

3. Mathematical model for allocating technical characteristics based on multi-failure modes correlation

After the total reliability of product is allocated to components, if the distribution of stress and intensity is known, the reliability index β corresponding to the reliability value of components can be obtained by looking up tables. β is used as the input of the failure mode reliability deployment space, the relationship matrix between failure mechanisms and fail modes will be established, the reliability loss of each failure mode will be assessed with considering of the impact of the correlation between failure modes. Then according to the size of the loss of reliability, the total reliability index β of the component will be allocated to failure modes.

If a failure mode i is independent, the causing reliability loss is FL_i, there is

$$FL_i = w_j u_{ij} \tag{1}$$

w_j is reliability loss weight of failure mechanism j corresponding with the failure mode i; u_{ij} is the correlation coefficient between failure mode i and failure mechanism j.

Suppose soft failure mode i directly leads to k association failures $k = (1, 2, \cdots, m)$ corresponding to t failure mechanisms $t = (1, 2, \cdots, m)$, considering the single layer chain effect, the calculating equation for reliability loss of failure mode i can be obtained.

$$FL_i = w_i \cdot u_{ij} + \sum_{\substack{k=1 \\ t=1}}^{m} p_{ik} \cdot w_t \cdot u_{kt} \tag{2}$$

Where, $p_{ik} = 1, \forall i = k$; p_{ik} is the probability that soft failure mode i raises the associated failure mode k; w_t is the reliability loss weight of failure mechanism t corresponding to failure mode k; u_{kt} is the correlation coefficient between failure mode k and failure mechanism t.

Considering the matrix structure of the house of reliability, and considering the propagation effects of multilayer failure modes, equation (2) can be expressed in the form of matrices

$$\boldsymbol{FL} = \left[\boldsymbol{W}^T \boldsymbol{U} \right] \left[\boldsymbol{P} + \left(\boldsymbol{P}^2 + \cdots + \boldsymbol{P}^f \right) \left(1 - \boldsymbol{I}_{mn} \right) \right] \tag{3}$$

$p_{ik} = 1, \forall i = k$; $\boldsymbol{FL}$ is $1 \times m$ reliability loss vector; $\boldsymbol{P}$ is $1 \times m$ autocorrelation matrix; $\boldsymbol{W}$ is $n \times 1$ weight column vector; $\boldsymbol{W}$ is $n \times m$ relation matrix. f is the layer of the failure chain.

It can be seen from equation (3) that the longer the failure chain is, the greater the accumulated reliability loss is, for a failure mode which is the initiator of the failure chain. The reliability index allocation coefficient can be acquired by normalizing the obtained reliability loss of failure modes as shown in equation (4). The greater the reliability loss of failure mode is, the larger the reliability index allocation coefficient is.

$$\alpha_i = 1 + \frac{FL_i - FL_{i0}}{\sum_{i=1}^{s} FL_i} \tag{4}$$

Where FL_{i0} represents the loss of reliability when the correlation of failure modes is not be considered, s is the number of failure modes that constitute the propagation chain, the deployment value β_i^* of reliability index for each failure mode can be calculate by equation (5)

$$\beta_i^* = \alpha_i \cdot \beta \tag{5}$$

β is the reliability index of the whole part. According to the information of HOR, the main failure mechanisms corresponding to β_i^* can be obtained, the β_i^* and the corresponding main failure mechanisms are input into the technical characteristics deployment space, and then deploy the technical characteristic values using the inverse reliability method.
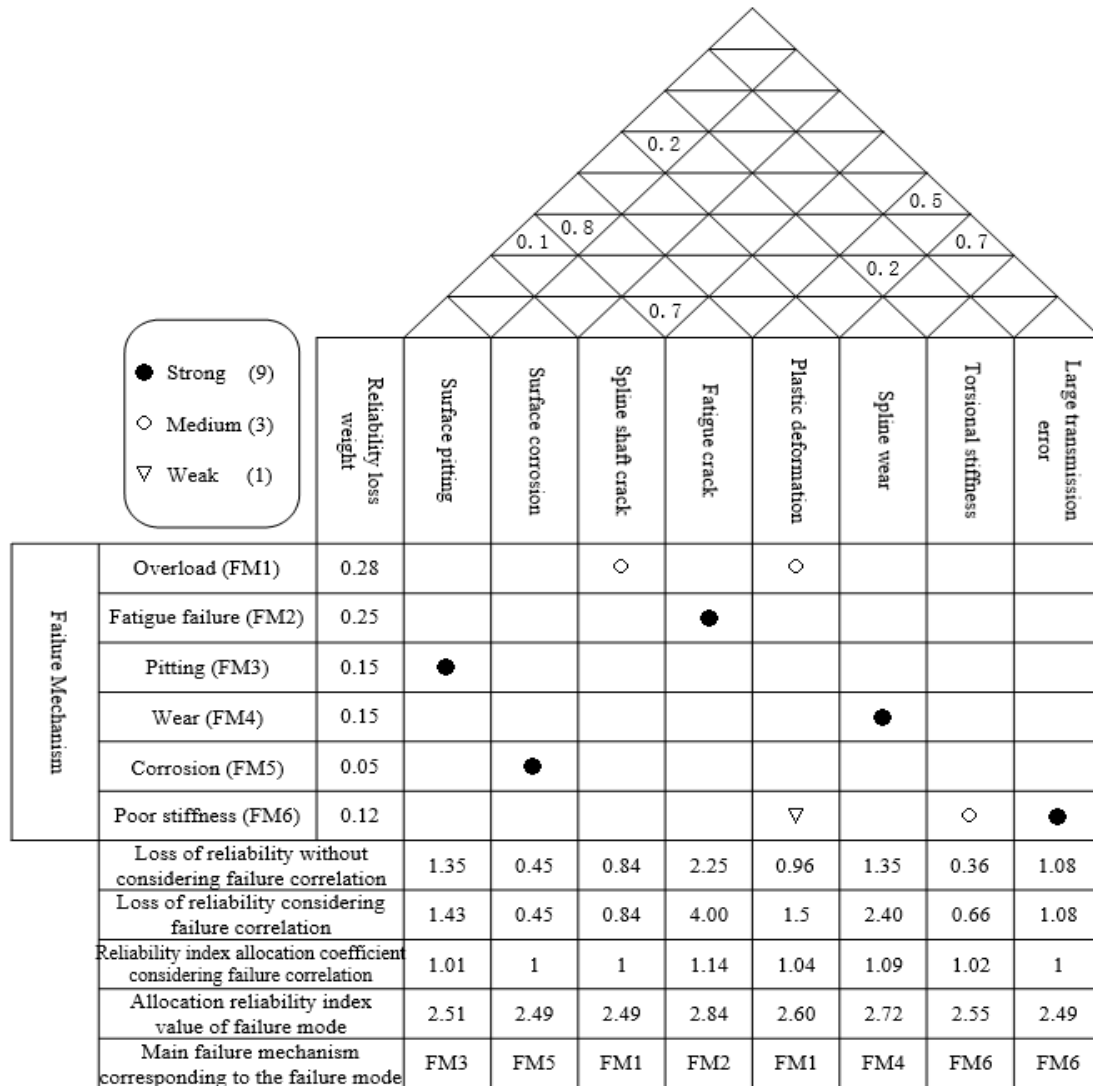
4. Case study

In this paper, a spline shaft in the driving system of one vertical machining centre is selected as an example. Through the analysis of the failure data of the machining centre collected from August 2008 to December 2009 and the FMECA, the corresponding house of reliability of the failure modes and house for allocating technical characteristics of the components can be established.

Known conditions of the spline shaft: the transmitting torque: $T=9500N\cdot m$, $\sigma_T =400$N·m. The bending moment of dangerous section is 5710N·m, $\sigma_M =250$N·m. The shaft material is 45 steel quenched and tempered, material strength is $\mu_S =600$MPa, $\sigma_S =60$MPa. The shaft is subjected to stable cyclic strain, the reliability of the spline shaft during 1000h operation is R= 0.993688. It is assumed that the stress and strength distribution of the spline shaft are normal distribution, and the reliability index value of spline shaft can be obtained by looking up the table: $\beta =2.49$.

4.1   Build the house of reliability for failure modes of spline drive shaft

The 8 failure modes of the spline shaft are obtained by FMECA, and the house of reliability of the spline shaft failure modes is established as shown in figure 2.

	Reliability loss weight	Surface pitting	Surface corrosion	Spline shaft crack	Fatigue crack	Plastic deformation	Spline wear	Torsional stiffness	Large transmission error
Overload (FM1)	0.28			○		○			
Fatigue failure (FM2)	0.25				●				
Pitting (FM3)	0.15	●							
Wear (FM4)	0.15						●		
Corrosion (FM5)	0.05		●						
Poor stiffness (FM6)	0.12					▽		○	●
Loss of reliability without considering failure correlation	1.35	0.45	0.84	2.25	0.96	1.35	0.36	1.08
Loss of reliability considering failure correlation	1.43	0.45	0.84	4.00	1.5	2.40	0.66	1.08
Reliability index allocation coefficient considering failure correlation	1.01	1	1	1.14	1.04	1.09	1.02	1
Allocation reliability index value of failure mode	2.51	2.49	2.49	2.84	2.60	2.72	2.55	2.49
Main failure mechanism corresponding to the failure mode	FM3	FM5	FM1	FM2	FM1	FM4	FM6	FM6

Legend: ● Strong (9)   ○ Medium (3)   ▽ Weak (1)

Figure 2. The house of reliability for spline shaft failure modes

HoR assigns the reliability index value β =2.49 to the failure modes through matrix operation, and finally output the deployment value β_j^* of failure modes reliability index and the corresponding main failure mechanisms.

The relationship between the failure mechanisms of the spline shaft and the soft and hard failure modes can be clearly expressed in the $n \times m$ matrix, which is shown in figure 2. In the two-dimensional plane of autocorrelation matrix, there are following propagation paths:

(a) Fatigue crack $\rightarrow$ Spline shaft crack

(b) Fatigue crack $\rightarrow$ Surface pitting $\rightarrow$ Spline shaft crack

(c) Spline wear $\rightarrow$ Surface pitting $\rightarrow$ Spline shaft crack

(d) Spline wear $\rightarrow$ Large transmission error

(e) Torsional stiffness $\rightarrow$ Plastic deformation $\rightarrow$ Large transmission error

In the above failure paths, the maximum order of cascading failure modes is $f = 2$. Using the equation (4) to calculate the reliability loss FL of each failure mode under the consideration of correlations, it can be found that the three failure modes: fatigue crack, torsional stiffness, and spline wear have a greater increase for loss of reliability.

4.2   Technical characteristics integrated deployment for spline shaft

According to the output of reliability deployment house of the spline shaft, it can be found that the fatigue crack and spline wear make greater loss to reliability of spline shaft, and the spline shaft diameter d and the life for wear of spline shaft t are the corresponding design parameters. Therefore, this paper established the connection equation for failure modes fatigue crack and wear of the spline transmission shaft, solved the deployment value of corresponding design parameters using the inverse reliability method.

4.2.1 Technical characteristics deployment of reliability for fatigue crack

In this case, the area which is easy to form fatigue crack is the spline. Due to the specific parameters of the spline shaft (such as the number of teeth, diameter, minor diameter, etc.) is not determined, the average diameter of the spline part d is chosen as the deployment parameter.

The limit state equation can be expressed as

$$G(X) = S - s = S - \frac{32}{\pi d_2^3}(M^2 + \alpha T^2)^{\frac{1}{2}}$$

(6)

Where the α represents the coefficient of the type of the cyclic stress. According to 3σ law, the strength limit of the material is $\delta = 600 \pm 180 MPa$, $S = \delta_{\min} = 420 MPa$. The shaft is rotated in one direction and thus subjected to pulsating cyclic stresses, $\alpha = 0.6$.

Known conditions: $\delta_T = 400 N \cdot m$, $\sigma_m = 250 N \cdot m$, $\beta^* = 2.84$. The mean value of M and T is the initial value for iteration, $T_0^* = 9500 N \cdot m$, $M_0^* = 5710 N \cdot m$, take the shaft diameter $d^* = 200 mm$ as initial value for iteration, repeat the iteration until the calculated value of the shaft diameter meets the condition of convergence, finally get the deployment value of shaft diameter is 199.7204mm.

Table 1 is a comparison of the calculated results with traditional probabilistic design method and the probabilistic design method considering multiple failure modes. It can be found that due to considering the extra reliability loss caused by the correlation of failure modes, deployment value of shaft diameter increase from 187.8311mm to 199.7204mm, increased by 6.2%.

Table 1. Comparison of calculation results(unit: shaft diameter-mm)

		Allocation Method	
		Traditional Probabilistic Design	Probabilistic Design for Multiple Failure Modes
Original Reliability	R	0.993688	0.993688
Original Reliability Index	β	2.49	2.49
Allocation Coefficient of Reliability Index	α_i	1	1.14
Allocation Value of Reliability Index	β^*	2.49	2.84
Shaft Diameter	d	187.8311	199.7204

4.2.2 Reliability technical characteristics deployment for wear failure
Through the same method, the wear life of the spline shaft was calculated. The wear life declines from $331h$ with traditional probabilistic design method to $318h$, reduced by 3.8%.

5. Conclusion
This paper proposed a comprehensive deployment method for reliability technical characteristics based on the correlation analysis of multiple failure modes. This method used the matrix structure to describe the transmission relationship among failure mechanisms. And a mathematical model calculating the reliability loss of each failure mode was established with considering the correlation between them. The reliability losses were normalized to obtain reliability index coefficient of each failure mode, established the technical characteristics deployment space and finally assigned reliability index to failure modes. The inverse reliability method was introduced to the calculation model for technical characteristics to do the comprehensive deployment for the technical characteristic. And the method was applied to the reliability design of the spline shaft in the transmission system of a machining centre, the example shows that the method can effectively adjust and optimize the results of the conventional probabilistic design. The following research will focus on the matching of design parameters and conflict resolution, as well as the corresponding algorithm implementation.

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